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Preface

The objective of this series is to review progress in soil and crop science and developments in agronomic practice. This volume contains ten chapters on a diversity of topics. Ordinarily the subjects selected for treatment are unrelated. However, in this issue four of the chapters that deal primarily with soils do have a connecting link because their origins lay in a conference in 1954 attended by a considerable group of agronomists who met to attempt a re-evaluation of the place of microbiology in soil science. Many soil processes are essentially microbiological, and the activities of the soil population may affect the welfare of the plant in numerous ways. Although the nutritional aspects are most readily recognized even these may be less straightforward than has often been claimed. The biochemistry of the rhizosphere is as yet most imperfectly understood, although all root-soil interactions take place in this zone. Four chapters (Martin *et al.*; Wadleigh, Allison, and Norman) stemmed from presentations made at the Soil Microbiology Conference, and another (Joffe) may have been influenced by the discussions that developed there.

Once again there is a review of the agronomic scene elsewhere than in North America. Åberg has summarized the trends in crop production in Sweden, and the achievements of Swedish agronomists particularly in the field of crop improvement through breeding of varieties better adapted to those bleak northern latitudes.

Another crop improvement story is that of the sugar beet in the United States recounted by Coons *et al.* The successful establishment of the beet sugar industry has depended on the incorporation of different characteristics into those European varieties which, although successful in Europe, were ill-adapted here.

Basic to all crop improvement programs, however, is the search for new germ plasm, its importation, propagation and screening. The activities of the U. S. Department of Agriculture along these lines through the years are not well known, and the article by Hodge and Erlanson on the Plant Introduction Section may help to remedy this deficiency.

This also is an unusually nitrogenous volume, but for this no apol-

ogy is necessary because crop yields are more directly related to the supply of nitrogen than to that of any other nutrient element. Many soil management practices, developed more or less empirically, are effective because of their influence on nitrogen availability and supply, particularly on older agricultural soils. Harmsen and van Schreven have comprehensively reviewed the information on the mineralization of organic nitrogen in soils, and this chapter may appropriately be read in conjunction with those by Joffe and Allison, on green manuring and nitrogen balances in soils, respectively.

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Ann Arbor, Michigan
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Soil Aggregation

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I. Introduction

The physical properties of soils influence plant growth through their effects on soil moisture, soil air, soil temperature, and mechanical impedance to root development and shoot emergence (Shaw, 1952). If the physical condition of a soil is of such a nature that plant roots or water does not readily penetrate it, or that germinating seed cannot break through a soil crust, then crop yields will be reduced, even though the soil may be adequately supplied with plant nutrient elements.

From the physical point of view the ideal soil is one in which the smaller mechanical fractions of sand, silt, and clay are bound into water-stable aggregates or granules. A soil of this type does not crust as readily, allows relatively rapid infiltration of precipitation and irrigation water, and is not as subject to the ravages of erosion. Furthermore, it can be worked easily, is better aerated, drains quickly, and permits greater root respiration and microbial activity (Page and Bodman, 1952; Russell and Russell, 1950).

In spite of the importance of the subject of aggregation to agriculture and much excellent work that has been done, our knowledge of the processes by which soil particles are caused to aggregate together and the forces which keep them aggregated is limited and often apparently contradictory. It is generally agreed that organic matter plays a key role in soil aggregation and most workers have apparently concluded that the main effect is cementation. Others have suggested that organic matter serves to waterproof the soil, thus preventing further breakdown of already formed aggregates.

There has been some study and much speculation concerning the nature of the organic compounds involved in the production and stabilization of aggregates. A lignin-protein complex was once thought to be the important constituent. Others have emphasized the waxes and resins as well as the sticky mucilage-like complexes found in soil organic matter. Recently much attention has been directed to the polysaccharides.

Several workers have attempted to assess the direct role of microorganisms in producing soil aggregates. It has been demonstrated repeatedly that aggregation increases in almost direct proportion to the numbers and activities of microorganisms. It has in fact been shown that some organic residues are not effective in producing aggregation except when microorganisms are abundant and activity is high.

Clay has usually been listed as an essential constituent of aggregates, but there has been little work reported which evaluates the role of clay in the formation and stabilization of soil aggregates. Iron, alu-

minum, and silicon oxides, and hydrated oxides are also thought to play an important part in stabilizing aggregates, but the mechanisms involved have not been clearly elucidated.

It is becoming increasingly apparent that there is no simple explanation for soil aggregation. Attempts to find an explanation on the basis of maintaining a high level of microbial activity are most certainly important where one is considering short-time effects, but it remains to be seen how much lasting improvement can be effected by these methods. The problem is extremely difficult, and the factors affecting the process are many and complex. However, the possibility of being able to evaluate structure in terms of the effects on plant growth, to measure the results of specific treatments, and to predict the result of field management practices are goals which should be worthy of the best efforts of soil scientists.

In this report soil aggregation will be discussed with emphasis on three aspects of the subject: first, mechanisms and processes involved in the formation of aggregates, with particular emphasis on the role of clay; second, the role of microorganisms and products of microbial activity; and third, the action of synthetic soil conditioners in stabilizing aggregates.

II. Formation and Stabilization of Aggregates

1. *Definition*

As is well known, many workers use the term "soil structure" and "aggregation" interchangeably. Emphasis on the pedological or morphological point of view may warrant such an approach, but in terms of the influence of physical properties of the soil on plant growth, such a definition gives too much emphasis to the aggregates themselves. Several workers have studied the properties of aggregates, but there is little evidence that aggregates have any direct influence on plant growth except as they modify the pore spaces in the soil. By affecting porosity, aggregates change the physical and chemical environment in which plant roots grow. With this view in mind a soil aggregate can be defined as a naturally occurring cluster or group of soil particles in which the forces holding the particles together are much stronger than the forces between adjacent aggregates.

It is not enough, however, to define an aggregate. Three related characteristics are either expressed or implied when soil aggregation is being discussed: (1) the size and shape of the individual aggregates, (2) the configuration or arrangement of the aggregates within the undisturbed soil, (3) stability. Of these, most emphasis has been placed

on the first. This may be justified in some soils having exceptionally stable and characteristic aggregates which are highly resistant to destruction either by tillage or natural processes and which thus impart to the soils physical properties which do not change readily as a result of management. Some of the prairie and chernozem soils are striking examples of this type. In most soils, however, the aggregates are not resistant. The determination of the aggregate size distribution in such soils is probably meaningless (except as a measure of relative stability), since the size distribution obtained is, to a large extent, dependent on the treatment given during the determination.

The size and shape of aggregates as they exist in the soil would certainly be expected to have considerable influence on the pore spaces. It can be readily seen, however, that the same aggregates arranged differently will impart quite different size and continuity of soil pores within the root zone. The fact that fairly good agreement is usually obtained between degree of aggregation and crop yields indicates that physical characteristics do in general tend to be better where the soil is more highly aggregated. It is possible, although unusual, to have a highly aggregated soil which still has poor physical properties. This would result if the aggregates were themselves rather dense and packed closely together.

The second of the above aspects of aggregation is certainly the most important as far as plant growth is concerned; yet strangely it has received the least attention. Present methods of dissecting the soil to determine the size of individual units eliminate the possibility of determining the function of the aggregates in place except by inference.

The third factor, stability, is one which is of obvious importance and which has received considerable study, but in spite of this it is still not possible to make an accurate measurement of the stability of soil aggregates except on an empirical, relative basis. The ordinary wet sieve analysis measures relative stability more nearly than any other characteristic. It is difficult to interpret results of the analysis in terms of the stability one might expect under field conditions. However, by standardizing the conditions of the determination and repeating it on composite samples at different times, it has been possible to show general trends in the levels of aggregation through the growing season as a result of tillage or cropping. Much more certainly needs to be done in this area, but until we can arrive at a fuller understanding of the forces affecting aggregation and of the nature of the processes which cause aggregates to remain in the soil, it is doubtful that we can make much progress toward finding a better method for characterizing stability.

2. *Mechanisms Involved in Aggregation*

Three kinds of mechanisms have been proposed to explain the formation of aggregates in the soil: (1) living bacteria and fungi (and possibly actinomycetes) bind soil particles together; (2) gelatinous organic materials such as gums, resins, or waxes are thought to surround the soil particles and thus hold them together through a cementing or encapsulating action; and (3) the clay particles themselves cohere and thus entrap or bridge between larger sand and soil grains. All of these types of binding are undoubtedly important and they may operate singly or in combination to different degrees in different soils (Hubbel and Chapman, 1946; Kroth and Page, 1947; Martin, 1946; Martin and Waksman, 1940; Peterson, 1946; Russell and Russell, 1950).

The evidence supporting the first view is partly direct and partly circumstantial. Where the mycelia of fungi extend quite thoroughly through the soil the particles are entrapped and held together. This is apparent even with the naked eye, and under magnification small clumps of particles can be seen clinging to the mycelia. Since most colonies of bacteria growing on artificial media appear somewhat slimy and gelatinous, it has been deduced that bacteria in the soil may serve to bind particles together; this appears to be a greatly oversimplified explanation. In any case the binding action of the living microorganisms would disappear when the food supply is exhausted and the numbers of microorganisms decline. It is comparatively easy to demonstrate this action during the course of simple experiments in the laboratory, but it is difficult to determine how important it becomes under actual field conditions, where keener competition exists between the different microorganisms, and food sources are usually not as readily available. It is quite probable that aggregates which are formed as a result of the presence of *living microorganisms* are ephemeral and quite possibly of little importance in most agricultural soils. Certainly other explanations will have to be found to explain the long-lived stable structural aggregates commonly found in many soils even where readily decomposable organic matter is low and decomposition is not occurring rapidly.

As will be discussed in a later section, it can be argued quite justifiably that some organic compound or compounds which are synthesized during the process of decomposition or which are by-products of the decomposition process are actually the important factors in producing stable soil aggregates. The available evidence supports this view quite strongly, and several workers have directed their attention to determining the composition and characteristics of these compounds. Chief

attention has been directed toward the polysaccharides, of which the derivatives of uronic acid have been most intensely studied. These do appear to occur in rather large proportions during the process of active microbial decomposition and may play quite an important role in the formation of a kind of aggregate.

Most of the emphasis has been placed on the nature of the organic fraction involved in aggregation. This can be readily understood since most of the investigators have been soil microbiologists, but in terms of the over-all problem it now appears that the role of the clay particles has been unnecessarily minimized and that the nature of the combination between clay particles and the polar organic compounds needs to be investigated intensively. The importance of the clay in soil aggregate formation has been stressed by several investigators. Baver (1935), in a study of 77 different soils in the United States, correlated aggregation, clay content, organic matter, and exchangeable calcium. A very high correlation was found between the <0.005 mm. clay and the >0.05 mm. aggregates. The correlation was greater as the organic matter content decreased. At the higher organic matter contents the effect of the clay became insignificant. It was concluded that clay was important in stable aggregate formation in the soil but that organic matter was probably more important. Mazurak (1950) studied the aggregation of the inorganic fraction of Hesperia sandy loam. It was found that the 0.03 μ particles were associated with water stability of synthetic aggregates. The important factor in aggregation is probably the presence of some chemical compound or group of compounds which appears in one way or another during the process of decomposition and which then combines with the clay to help make aggregates.

The third proposed mechanism of aggregate formation involves the belief that clay is the chief binding agent, and that organic materials do not act primarily to hold the clay and sand and silt grains together. Rather their chief role may be to modify the forces by which the clay particles themselves are attracted to one another. According to this view, the cohesive force between clay particles rather than the cementing action of organic molecules is thought to be the binding force in aggregation. The magnitude of these forces between clay particles may be very great, leading even to solidification in some cases. This last condition would obviously be unfavorable for agriculture, but the same types of forces between clay particles appear to be involved in producing desirable structure in agricultural soils as are active in solidification of puddled soils.

The cohesive forces which may operate between clay particles to

hold them together may act in three ways: (1) by linkage due to chains of water dipoles; (2) by bridging or tying together with certain polar, long-chain, organic molecules; (3) by cross-bridging and sharing of intercrystalline ionic forces and interactions of exchangeable cations between oriented clay plates.

It is quite likely that the first of these (linkage due to water dipoles) is of importance under moist conditions and probably accounts for some of the resistance to dispersion observed in some soils. It is difficult to see, however, how such a mechanism may be active in causing or at least affecting orientation of adjacent clay particles as they are dried out. The second mechanism in which polar, probably long-chain, organic compounds hold clays together, may prove to be of great significance and certainly needs to be investigated more intensively. There is evidence that many such compounds can be strongly adsorbed by clays (Gieseking, 1949). It appears logical that they could serve as binding agents to hold soil particles together either by hydrogen bonding or direct bridging. It is known that different compounds vary tremendously in the degree to which they are held by clays and likewise that the clays differ in the force with which different polar compounds are adsorbed. Many such compounds are held tightly, and it has been reported that certain clay-organic complexes are resistant to redispersion or crushing after drying. The synthetic long-chain polymers which have been introduced for use in stabilizing soil structure have produced striking results with certain types of clay soils, and part of the action may be due to bridging of the type postulated above. The exact mechanisms by which these compounds are adsorbed to clay surfaces need to be investigated further, and it should not be concluded that they simply hold the soil particles together because of their apparent stickiness.

It is difficult to assess the importance of molecular binding forces in the soil at our present stage of knowledge. There is no question but that they are important. They may be the predominating forces under certain conditions. However, under a great many other conditions, it is believed that the intercrystalline ionic forces between clay particles may themselves account for all of the binding necessary to explain aggregation in the soil. It can readily be seen that under certain conditions cohesion between clay particles can give rise to extremely strong forces, which could account for all the binding observed in soils containing clays. These forces are at a maximum when the clay particles are in closest contact and in preferred orientation, so that the number of points of contact and areas of contact are large. Puddling of soils or clays

favors such orientation, and the pieces resulting after puddled clays are dried are strong and coherent. Crumbs resulting from drying of dispersed soils are usually much stronger than those from flocculated clays, since in flocs the tendency is for random orientation. In most agricultural soils which have not been mismanaged, clay particles will not yet have been strongly oriented. Natural structure may still be favorable and total cohesive force may not be high. With more nearly random orientation the number and area of points of contact should be at a minimum. Further, if, as is usually the case, water dipoles as well as active organic molecules are adsorbed on the free clay surfaces, the magnitude of any further cohesive forces which could become effective between clay particles will be even further reduced. Apparently the same types of bonds would be involved at existing points of contact of clay particles as in puddled soils. However, with part of the surface energy directed toward adsorption and orientation of water and organic molecules and with these molecules serving as a protective layer over free surfaces of the particles, any further expression of the normal cohesive forces would be markedly reduced. Thus these materials would act to stabilize the existing structure, partly through cementation and partly through modification of surface properties of the clay particles.

Swelling has been shown to cause the breakdown of aggregates under certain conditions. Many polar organic compounds when adsorbed greatly reduce the swelling tendency of clays. Presumably this is brought about because these compounds are preferentially adsorbed by the same forces on the clays which attract water dipoles. They are, however, much more tightly held. It should be emphasized that relatively small amounts of active organic material, even a monomolecular layer, may exert a tremendous influence on swelling, cohesion, and other physical characteristics of clays.

Clays differ in the surface activity and the ability to adsorb or orient water and organic molecules, and this is reflected in soil properties. They differ also in the magnitude of cohesive forces which would be exhibited even under complete orientation and contact. Adsorbed cations play an important role as well, presumably dependent upon the degree of hydration of the adsorbed cations and whether they cause dispersion or flocculation of the colloidal clay. It appears that soils which are predominantly kaolinitic may not exhibit as strong cohesive forces upon drying as are exhibited by soils which are predominantly montmorillonitic. It would be unsafe to generalize, however, since too little is known at the present time of the characteristics of the clay minerals in large numbers of soils. With either mineral type, granules formed by drying from highly hydrated monovalent systems are less

resistant to rehydration and dispersion than are those from soils saturated with slightly hydrated cations.

3. *Formation of Aggregates*

In the light of these considerations the following seems to best explain how aggregates are formed and stabilized in agricultural soils: aggregates result primarily from the action of natural agencies or any process by which parts of the soil are caused to clump together and separate from adjacent masses of soil. If soils are initially dispersed (as in alkali soils), flocculation is essential for aggregate formation; if they are partially puddled or solid, fragmentation into smaller units is the first essential. Thus, there are two kinds of processes involved. The first is concerned with the building up of aggregates from dispersed materials; the second involves the breaking down of larger coherent masses into favorably sized aggregates. Since most soils become more dense and compact with continued farming, the second case is of greater interest. Separation of parts of the soil mass may result because of: (1) the action of small animals, particularly earthworms; (2) tillage processes; (3) pressures and differential drying caused by freezing; (4) compression due to roots; (5) localized shrinkage caused by removal of water by roots or evaporation. Roots are undoubtedly tremendously important, acting to separate and compress small clumps of soil, to cause shrinkage and cracking due to desiccation near the root, and to make conditions favorable for the activity of microorganisms at the surfaces of these units. Alternate wetting and drying causes cracks or cleavage planes to develop owing to differential swelling and shrinking. Freezing causes extreme localized pressures, again tending to cause the soil to break up into rather small fragments or crumbs. When this occurs, forces within the crumb which cause clay particles to cohere are stronger than those between clay particles of adjacent crumbs. These units tend to exist separately in the soil until forced back into intimate contact with neighboring groups. The size and shape of the masses which are thus caused to form in the soil are extremely important but little is known of the factors governing the characteristics of the aggregates resulting or of the specific role of the different clay minerals.

The characteristics of the pore spaces in the soil obviously depend upon the shape, size, and arrangement of aggregates. It has been suggested that kaolinitic clays tend to produce platy aggregates in contrast to the blocky aggregates produced by montmorillonitic clays, but it is not felt that enough is known about the specific effects of these minerals to generalize at this time.

4. *Stabilization*

The structural units once formed in the soil would readily disappear and recombine with others in the soil if not stabilized. This is probably the chief role of the active organic compounds. As pointed out above and later, certain types of compounds and active groupings on organic compounds have been shown to be strongly adsorbed on clay colloids. The forces involved differ with the different compounds and different kinds of clay, as well as the adsorbed inorganic cations which are already present. Some compounds may be adsorbed as cations, others as anions, and others as molecules, the binding capacities in this latter case not appearing to be related to either anion or cation adsorptive capacities.

Strong adsorption of active organic molecules on clay surfaces would have a profound effect in modifying the forces between clay particles which cause the particles to cohere. Those particles within the aggregate where a degree of orientation and close contact had already occurred would be less affected than those on the outer surfaces, where clay surfaces would be exposed and available for adsorption. With outer surfaces essentially saturated or occupied with active organic compounds, but little residual force would be left which could act to cause coherence between clay particles of adjacent aggregates. In this situation the requirements for aggregates would have been met, namely, stronger cohesive forces between particles within the aggregate than between aggregates, and the unit could exist in the soil as a separate entity. Such a unit would tend to be stable, even when wet, if organic molecules were so strongly adsorbed that further hydration or swelling and consequent weakening of bonds between clay particles did not occur, or if the compounds themselves tended to hold adjacent clay particles together through cross linkage or mutual adsorption. Apparently both mechanisms are of importance, and it is probable that they operate concurrently.

Polar organic compounds may be thought of as playing two important roles in soil structure tending to stabilize naturally formed aggregates: (1) weakening the otherwise strong cohesive bonds between clay particles, thus permitting formation into aggregates instead of a solid mass; and (2) linking clay particles together through mutual adsorption of such compounds by two or more clay particles. There is insufficient evidence available to indicate which of these two functions is the more important. It is almost certain, however, that both are important and that both actions may occur concurrently in stabilizing soil structure.

Recent work with synthetic soil additives which will be presented in detail in a later section has shown that these highly polymerized straight-chain compounds are extremely tightly held by clays. They do not appear to be replaced by ordinary exchange and are quite resistant to microbial attack. It is significant that these materials will not create good structure but act instead to stabilize whatever structure is found when the material is applied. If the soil can be prepared into favorably sized aggregates or fragments, the materials do an effective job of stabilizing the aggregates so they do not tend to run back together upon further wetting.

Earlier literature stressed the importance of flocculation in soil structure, but it has been found that colloids in almost all nonalkali soils tend to be flocculated. Both Ca^{++} and H^{+} ions produce flocculation, and further, adsorption of most polar organic molecules causes complete flocculation. It is considered that most nonalkali soil clays are already flocculated and that changes occurring in soil structure are not primarily changes in degree of flocculation but rather in degree of expression of cohesive forces between already flocculated clay particles.

It should be re-emphasized that clays are essential in structure formation and that the primary role of organic matter is in modifying the physical properties of the clay. Since the mechanism involves an adsorption process, only very small amounts of the active compounds may be involved at any one time, but the effect on clay and hence on soil properties is tremendous. The amount and composition of the organic materials in the soil at any one time are dependent upon the activity of microorganisms, with the result that physical properties of the clay organic matter system may change rather rapidly. During decomposition the microorganisms themselves exert a direct and usually favorable effect on structure, but the effects produced through adsorption of the compounds produced are thought to be much the most significant. The specific organic compounds which combine with and modify the characteristics of the clay are not yet known, but their importance is tremendous, and studies of the nature of these compounds and the clay-organic matter combination should prove to be fruitful in helping us to arrive at an understanding of how aggregates are formed and stabilized. Following sections will discuss certain organic fractions found in soil and present evidence of the action of microorganisms in producing and stabilizing soil aggregates.

5. *Iron and Aluminum Oxides*

In addition to the mechanisms discussed in the preceding sections, oxides or hydrated oxides of iron and aluminum may serve as cement-

ing or binding agents in many soils. In lateritic or semilateritic soils, for example, iron, or iron and aluminum oxides are important binding substances. Lutz (1936) found a high positive correlation between the free iron oxide in lateritic type soils and aggregation. He suggested that the free iron serves a dual purpose, namely, that the iron in solution acts as a flocculating agent for the clays and the precipitated iron acts as a cementing agent. At the pH of the soils studied, the iron would be precipitated as a hydrated gel, which would become a good cementing agent upon dehydration. Studies by Weldon and Hide (1942) demonstrated that the amount of sesquioxides extracted from well-aggregated fractions of several prairie soils was considerably greater than that extracted from the poorly aggregated fractions. These investigators stressed the probability that sesquioxides act as cementing agents in the formation of aggregates in prairie soils as well as in lateritic soils.

Kroth and Page (1947) concluded from studies with the electron microscope that iron and aluminum oxides provide a continuous matrix which binds soil particles into secondary units by physical forces alone.

III. Effect of Organic Residues on Aggregation

1. Microbial Decomposition

The preceding section presented a generalized discussion of the possible mechanisms involved in the process of forming and stabilizing soil aggregates. With these considerations in mind a review of the literature and a discussion of the role of organic substances, microorganisms, and products of microbial activities in soil aggregation will be presented.

Numerous investigators have demonstrated an improvement in soil aggregation following organic matter applications. Although some complex organic materials may contain soil-binding substances, the increased aggregation has been shown to be largely contingent upon the decomposition of the residues by soil organisms. Under sterile conditions only slight to moderate benefit or none will ensue. For example, studies by Martin and Waksman (1940) and Peele (1940) demonstrated that when a microbial energy source such as sucrose or cellulose is added to a soil, and the soil is sterilized, no improvement in soil aggregation will take place. If the mixture becomes contaminated or is inoculated with a soil suspension or with certain soil microbes, however, a marked aggregating effect will follow upon incubation. Studies with complex residues such as alfalfa, grass, and cereal straws, on the other hand, demonstrated the presence of water-soluble soil-binding sub-

stances (Martin, 1942). The concentration or quality of the water-soluble materials increased during the early and intermediate stages of composting, and decreased during the later stages. When the materials were mixed with the soil and allowed to decompose, however, much greater aggregation occurred than that produced by the water extracts of the fresh and composted materials.

The importance to soil aggregation of organic substances which are apparently produced largely through microbial activity has been stressed by numerous investigators. Robinson and Page (1951) tested artificial aggregates of Brookston clay loam for resistance to slaking by the wet sieving procedure before and after oxidation of the organic fraction with hydrogen peroxide. The stability of the aggregates of the oxidized soil was very poor in comparison with the unoxidized soil. It was concluded that the organic matter associated with the clay was largely responsible for aggregate stability. Studies by Metzger and Hide (1938) and Weldon and Hide (1942) indicated that the organic matter content of several soils was much higher in the well-aggregated fractions than in the poorly aggregated fractions. Baver (1935) suggested that certain organic materials bind soil particles together through physicochemical processes. Several investigators have demonstrated the existence of organo-clay complexes (Ensminger and Gieseking, 1942; Springer, 1940; Myers, 1937). Ensminger and Gieseking (1939, 1942) found that certain proteins were adsorbed within the crystal lattice structure of montmorillonite type clays and that adsorption made them more resistant to enzymatic action. Bartholomew and Goring (1948) and Goring and Bartholomew (1950, 1951) worked with certain organic phosphorus compounds and found that decomposition was retarded by clay which adsorbed the phosphorus compounds. Fixation by the clays varied greatly depending on the nature of the organic compound, the type of clay, and the pH of the systems.

Kroth and Page (1947) made a study of natural and synthetic soil aggregates in which the electron microscope was utilized as one approach to the problem. All parts of the investigation indicated that the aggregating substances were uniformly distributed throughout the aggregates and in contact with each soil particle. No evidence of aggregate capsules or coatings was found. In a later study, Robinson and Page (1951) stated that the basis of aggregate stabilization by organic matter is a modification of the properties of clay. It was concluded from their work and that of others that the organic matter promotes aggregate stability by reducing swelling of montmorillonite-type clays and by reducing the destructive forces of entrapped air during wetting of

the soil; by decreasing wettability; and by strengthening the aggregate through colloidal organic depositions and development of fibrous material around and through the aggregate.

It appears evident that clay and organic complexes do undergo physicochemical reactions (Broadbent, 1953). These reactions probably influence soil aggregate stability.

During periods of intense microbial activity the soil organisms themselves may mechanically bind soil particles together (Waksman, 1916; Waksman and Martin, 1939; Martin and Waksman, 1941; McCalla, 1942). Under such conditions the binding action of fungus filaments, for example, can be seen with the eye or better with the microscope. Hubbel and Chapman (1946) concluded that living organisms were the most important factor in binding soil particles together and that organic substances produced by microbial activity were not important. This view is not supported by most investigators (Myers and McCalla, 1941; Pohlman and Nottingham, 1941). Strong evidence against it was obtained by Martin and Aldrich (1952) in a study of the influence of soil fumigation on aggregation. The numbers of organisms in treated soils, following an initial decrease, attained levels as high as 14 or more times those in the untreated soils. The kinds of organisms also varied. In an acid soil, fungi predominated, whereas in neutral and alkaline soils bacteria and actinomycetes predominated. There was no correlation between types or numbers of organisms and aggregation, indicating that it is not numbers of microbes which are most important in soil aggregation, but more likely products of their activity during decomposition of added organic materials.

The increased soil aggregation which takes place during the microbial decomposition of organic residues in the soil probably results from chemical and physical interactions among certain products of decomposition of the organic matter, substances synthesized by the soil microbes, and the soil particles. In addition, a mechanical binding of the soil particles by microbial cells and filaments during periods of intense microbial activity in the soil may be involved to a limited extent.

2. *Influence of Kind and Amount of Organic Material*

Investigations by Browning and Milam (1944), Kroth and Page (1947), Martin and Waksman (1940, 1941), and Martin (1942) have shown that, in general, materials containing relatively large amounts of readily decomposable constituents exert the greatest and quickest aggregating effect; somewhat more resistant materials require a longer time to exert their maximum aggregating influence but continue to be effective over a longer period of time; and extremely resistant or relatively

inert substances, such as well-composted materials, certain lignified wood by-products, and some peats, have little or no influence on aggregation. In the study by Martin (1942), the aggregating effect of various organic residues or mixtures of residues was tested before, during, and after composting for 200 days. After the first period of composting the aggregating effect was less than that of the original residues, and after the 200-day period the binding action was still less. This and the other studies emphasize the importance of the decomposition process in soil aggregate stabilization.

The level of aggregation attained following organic matter applications is also dependent upon the amount of residue applied and the state of aggregation of the soil to which it is applied (Browning and Milam, 1941, 1944). In general, large applications are more effective than small, and aggregation is increased more in a soil which is poorly aggregated owing to lack of organic matter than in one which is well aggregated.

Growth of various crops in the soil affects aggregation. Johnston *et al.* (1942) studied the influence of various cropping systems on soil aggregation. Bluegrass sod was most effective in maintaining stable soil granulation. Other crops in order of decreasing effectiveness were clover, oats, rotation corn, and continuous corn. Metzger and Hide (1938) reported that alfalfa and sweet clover leave the soil in a better state of aggregation than do several other nonsod crops. All evidence indicates that sod crops increase or maintain soil aggregation better than most or all other crops (Strickling, 1951). This is no doubt associated with the amount of root residue left in the soil which can be utilized as microbial energy material, with the good distribution of the root residues throughout the soil mass, and with the action of the root system in breaking up soil lumps into smaller units.

After a single application of organic material is applied to the soil, aggregation reaches a maximum and then declines. Although the effects of a single large application may last for periods of a year or longer, in order to maintain good aggregation, periodic addition of organic materials is necessary.

The work and views of F. Y. Geltzer with respect to organic matter, soil microbe, and soil structure relationships have been quite widely quoted (Stallings, 1952; Russell and Russell, 1950; Bremmer, 1954). It is Geltzer's opinion (1944) that the best structure is produced in a soil during the decomposition of fungal hyphae by soil bacteria. According to her theory, organic materials are first attacked by soil fungi which produce substances with little aggregating power. The fungal hyphae are then attacked by soil bacteria which produce gummy substances

which combine with the clay particles upon their release by autolysis of the bacteria. It is these substances that supposedly form the stable aggregate structure. It is probable that bacteria decomposing fungus cell material do produce soil-binding substances, but it is unlikely that they would produce or synthesize certain kinds of organic substances while decomposing fungus cell material and different substances while decomposing plant or other types of complex organic residues. In addition, as will be pointed out in a later section, the fungi as a group are just as effective or more effective than the bacteria in binding soil particles into water-stable aggregates. It is probable that certain microbes from all groups are important in the soil aggregation process and that a complex energy material is, in general, more important than the source of the energy material.

Alderfer and Merkle (1944) found that mulches increased soil aggregation in the field when decomposition of the mulch material occurred. The fact that decomposing plant residues contain water-soluble aggregating materials suggests that improved soil structure following mulching may be due to the leaching into the soil of water-soluble binding substances from the surface residues. In the absence of leaching which would occur during rains, sprinkler irrigation, or irrigation, aggregation of the surface soil could result from the decomposition of the mulch material in contact with the surface.

3. *Influence of Environmental Conditions*

The effect of factors such as temperature and moisture on the aggregating action of organic residues has received little attention. A study by Martin and Craggs (1946), however, clearly indicated that the beneficial action of organic residues on soil structure is markedly influenced by environmental conditions. Typical results are presented in Table I. In general, as the temperature of incubation increased, the aggregating action of the residue decreased. At low temperatures a longer incubation period was required for maximum aggregation to take place. The temperature effect may be explained in two ways. In the first place temperature will affect the nature of the microbial population involved in the decomposition processes. It is possible that the microbial population active at low temperatures produces a greater quantity of, or better quality, aggregating substances than those active at high temperatures. On the other hand, it is well known that high temperatures favor the rapid decomposition of organic substances (Waksman, 1938; Waksman and Gerretsen, 1931). It is possible that at elevated temperatures effective organic aggregating substances are produced through the activities of the microbes, but that these sub-

TABLE I

Influence of Temperature and Moisture on Soil-Aggregating Effect of Organic Residues in Declo Loam[1]

Treatment	Percentage aggregation of <50-μ particles at various incubation periods, days						
	Effect of temperature[2]				Effect of moisture[3]		
	10	20	50	100	10	20	50
	10° C.				*25% of saturation*		
Control	30	31	32	33	36	36	36
Alfalfa	60	71	73	68	70	70	69
Cow manure	37	41	44	45	52	55	53
Alfalfa-grass hay	56	67	70	66	68	64	64
Sucrose	71	73	66	59	72	73	71
	25° C.				*50% of saturation*		
Control	31	31	32	31	32	33	32
Alfalfa	69	66	66	58	69	67	62
Cow manure	46	53	56	54	51	53	56
Alfalfa-grass hay	66	67	64	57	66	71	65
Sucrose	70	68	58	50	73	70	67
	40° C.				*75% of saturation*		
Control	32	31	29	30	30	32	32
Alfalfa	67	58	57	54	61	63	59
Cow manure	52	55	53	46	49	53	55
Alfalfa-grass hay	59	57	56	51	60	65	64
Sucrose	58	54	51	46	67	57	53
	55° C.				*Saturated*		
Control	30	32	30	31	29	28	31
Alfalfa	49	50	43	41	48	38	36
Cow manure	48	47	47	43	38	38	40
Alfalfa-grass hay	52	53	50	41	46	45	43
Sucrose	48	47	41	34	53	45	38

[1] Martin and Craggs (1946).
[2] Moisture content maintained at 55% of capacity.
[3] Temperature of incubation 25° C.

stances are in turn quickly destroyed by further microbial activity. The shorter period of incubation required for maximum aggregation at the higher temperatures, followed by more or less rapid decline (Table I), tends to support this view.

Several workers have indicated that aggregate stability of field soils may be subject to seasonal variation (Alderfer, 1946; Wilson and

Browning, 1946; Wilson *et al.*, 1948). Strickling (1951) reported large seasonal variation in 1949 but not in 1947 and 1948. It was observed that 1949 was one of the hottest and most humid years on record, and it was suggested that the climate may have stimulated the decomposition of organic aggregate-stabilizing substances by the soil organisms.

In soil saturated with water (Martin and Craggs, 1946), the beneficial action of organic residues in aggregating the soil was greatly reduced. In a waterlogged soil the activities of the fungi and strictly aerobic bacteria are greatly retarded. Decomposition is carried on primarily by anaerobic bacteria. It appears that the latter population does not produce the quantity or quality of soil-binding substances produced by the population of a well-drained soil.

IV. Effect of Microbial Species on Aggregation

Pure culture studies have demonstrated that microbial species vary widely in their ability to bind soil particles. In one study, using sucrose as an energy source, *Aspergillus niger* and *Azotobacter indicum* were much more effective than *Rhizopus nigricans* or *Pseudomonas fluorescens* in binding the soil (Waksman and Martin, 1939). *Cunninghamella blakesleeana* proved to be more effective than a bacterial culture in a study by Peele (1940). McCalla (1946) studied the effect of different microbial groups in increasing the stability of soil lumps against falling water drops. The order of decreasing effectiveness was fungi, actinomycetes, certain bacteria, yeasts, and the majority of bacteria tested. The presence of organisms of low stabilizing power reduced the effectiveness of organisms which produced high stabilization. In another study, a *Cladosporium* sp. was much more effective than *Mucor* or *Rhizopus* species in binding the soil particles (Martin and Anderson, 1942). Gilmour *et al.* (1948) reported that the binding ability of various fungus species depended to some extent on the soil and on the source of energy material used.

Inasmuch as soil organisms vary in growth habits, structural makeup, decomposition products formed, and substances synthesized, it would be expected that their effect on soil granulation would vary.

V. Nature of Organic Soil-Binding Substances

Increased soil aggregation following organic matter application could be brought about by one or more of the following:

1. Mechanical binding of the soil particles by microbial filaments or cells during periods of intense microbial activity.
2. Presence of binding substances in the organic residues.
3. Organic waste products formed during the decomposition of the

original material, dead microbial cells, or secondary decomposition products.

4. Organic binding substances synthesized by the soil organisms.

Which of these are the most important is a matter of conjecture, but the last two are probably very important if not the most important. Geltzer (1937) came to the conclusion that during the decomposition of organic matter in the soil there is an accumulation of synthetic microbial substances which bring about the binding of soil particles into aggregates. Peele (1940) demonstrated that bacterial mucus from several species produced water-stable aggregates when incorporated with the soil.

1. *Polysaccharides*

In a study designed to determine the nature of soil-binding substances synthesized by soil organisms, a polysaccharide of the levan type produced by *Bacillus subtilis* was found to be effective binding material (Martin, 1945). In a continuation of this study (Martin, 1946), several bacterial polysaccharides were found to be very effective binding agents (see Table II). As little as 0.1 g. of one material in 100

TABLE II

Effect of Bacterial Polysaccharides on Aggregation of Declo Loam[1]

Polysaccharide	Concentration, %	Aggregation of <50-μ particles, %
None	—	28
Fructosan from *Bacillus subtilis*	0.1	44
	0.3	51
Fructosan from *Azotobacter indicum*	0.1	59
	0.3	65
Dextran from a soil bacterium No. 1	0.1	60
	0.3	63
Dextran from a soil bacterium No. 2	0.1	70
	0.3	75
Dextran from *Leuconostoc dextranicum*	0.1	56
	0.3	66

[1] Martin (1946).

g. soil bound 23 g. of dispersed silt plus clay into water-stable aggregates larger than 50 μ in diameter. Related studies carried out in England by Geoghegan and Brian (1946, 1948) demonstrated the marked binding action of microbial polysaccharides. In the first report, a relationship between the nitrogen content of the polysaccharide and its aggregating effect was indicated, namely, the preparations containing 0.2 to 0.3 per cent or more of nitrogen were more effective than those containing less than 0.1 per cent. Later (1948) this was shown to be due to a degradation of the material during purification.

The investigators who have reported the influence of microbial polysaccharides on soil binding have emphasized that these compounds are undoubtedly not the only materials produced through microbial decomposition processes which aid in soil aggregation, but that they are probably important because similar type compounds are apparently present in soil humus. It has been estimated that from approximately 5 to 20 per cent of the soil organic matter consists of polysaccharide substances, primarily of the polyuronide type (Norman and Bartholomew, 1943; Shorey and Martin, 1930). The fact that marked aggregation of soils results from applications of polysaccharide concentrations which are less than that apparently found in many soils suggests that these materials may play an important function in soil granulation.

The polysaccharide fraction of the soil could be derived from plant polysaccharides, microbial polysaccharides, or both. During the decomposition of plant residues in composts, the cellulose fraction almost completely disappears, whereas a large amount of other types of polysaccharides, primarily polyuronides, remains in the residue (Waksman, 1938). It was suggested that some of the plant and synthesized microbial polyuronides are somewhat resistant to decomposition and therefore persist in the residue. On the basis of decarboxylation rate curves of soil organic matter and bacterial gums, Fuller (1946, 1947) suggested a microbial origin for the soil uronides.

Bremmer (1950) believes that the estimates of polyuronides in the soil are impossibly high and is of the opinion that the method for estimating soil uronic carbon, which involves prolonged boiling with 12 per cent HCl, splits off carbon dioxide from other soil constituents. In this connection, Broadbent (1953) points out that the carbon content of the organic matter of most surface soils is approximately 50 per cent, whereas that of pure uronide is 40.9 per cent. Any increase in the polyuronide fraction would lower the carbon content of the organic fraction. Actually, the carbon content of the soil organic matter decreases with depth, whereas the polyuronide content estimated by the

usual procedures increases; this is indirect evidence that the procedure has merit. Broadbent further states that the exchange capacity of the organic matter increases with depth, indicating more acidic groups.

Recently, Forsyth (1950) isolated two polysaccharides containing uronide constituents from soil organic matter. Stevenson *et al.* (1952) found polysaccharide components including galacturonic acid in the hydrolyzate of organic colloid from soil. These findings further support the belief that the polysaccharides constitute an important fraction of the soil organic matter and could, therefore, contribute to soil aggregation under field conditions. Additional evidence of the possible importance of the soil polysaccharides was obtained by Swaby (1950), who noted that the binding action of humus extracts was destroyed by acid or alkaline hydrolysis; this suggests the importance of proteins, polysaccharides, or both.

Most plant and microbial polysaccharides are subject to rapid attack by soil organisms (Norman and Bartholomew, 1940; Martin, 1946). Their persistence in the soil has been attributed to a possible combination with other soil constituents including clays which render them more resistant to microbial attack (Norman and Bartholomew, 1943; Martin, 1946; Fuller, 1947).

2. *Other Organic Substances*

In addition to microbial polysaccharides, some plant polysaccharides, certain modified lignins, proteins, oils, fats, and waxes, which are related in chemical composition to microbial decomposition products, or synthesized compounds have been found to increase the stability of soil aggregates. Alginates have been tested by Hedrick and Mowry (1952), Quastel (1952), and others. Geoghegan (1950) found pectin and alginic acid to be effective bindings agents in an acid soil but not in soil saturated with sodium or calcium. McCalla (1950) reported that egg albumin, casein, and certain oils, fats, waxes, and resins increased structural stability but other proteins and various carbohydrates did not. In a study by Martin (1946), certain microbial polysaccharides were found to be better aggregate stabilizers than were white pine lignin or casein, although the lignin and casein produced a rather marked binding action. In this study, it was necessary to get the lignin in solution before it would bind the soil particles. Oxidation of humus extracts (Swaby, 1950) with hypoiodite, which is supposed to destroy lignin-like compounds but not polysaccharides, reduced the binding action of the extracts. This provides indirect evidence that lignin-like colloidal materials contribute to the binding action of soil humus.

More work is needed to evaluate the contribution of a variety of natural organic substances to soil aggregate stability and to determine the nature of the clay-organic matter complex.

VI. Synthetic Soil Conditioners

1. *Nature of Materials Used*

The discovery that soil microorganisms synthesized polysaccharides and other compounds which enhanced soil granulation stimulated the search for synthetic compounds which would act in a similar manner to the natural products but would persist for longer periods of time in the soil. The alginates, which are similar to some bacterial polyuronides, were used first for structural improvement (Quastel and Webley, 1947; Hedrick and Mowry, 1952; Quastel, 1952, 1953) but with only fair success. Several tons of material per acre were required, and it was so readily decomposed that it lasted for only a short time in the soil; in addition it reduced the available nitrogen content to deficiency levels.

The silicates of potassium and sodium have been tested by Dutt (1947), Laws and Page (1946), Raney (1953), and others; waterproofing chemicals such as stearic and abietic acid, by McCalla (1946b) and Winterkorn *et al.* (1945); and volatile and water-soluble silicones, by Van Bavel (1950). All have increased soil granulation, but they are currently not being used in the field except possibly for certain engineering purposes because usually high rates of application are needed, with resulting high alkalinity, waterproofing effects, and toxicity to soil microorganisms. In addition the silicones are applied with difficulty and are costly. Satisfactory effects of these compounds on crop growth have not been established.

Certain cellulose esters have been used successfully for structural improvement of the soil. Among these are cellulose acetate, cellulose methyl ether, methyl cellulose, carboxymethyl hydroxyethyl cellulose, and the variously substituted carboxymethyl celluloses (Felber and Gardner, 1944; Quastel and Webley, 1947; Hedrick and Mowry, 1952; Martin and Kleinkauf, 1951; Raney, 1953). These compounds act very much like the natural polysaccharides and are capable of bonding directly to the silts and clays to effect an immediate improvement in soil granulation. Aggregate stability is largely a function of the degree of substitution on the cellulose molecule. The materials are, however, subject to decomposition by the soil microflora, so that induced changes tend to be of short duration. Unpublished work with carboxymethyl cellulose at Ohio State College by P. E. Baldridge, J. J. Doyle, and G. S. Taylor has shown that increases in the lower

plastic limit and intrinsic permeability of Hoytville clay and Miami silt loam occur at concentrations of from 0.025 to 0.50 per cent by weight, and that substitution of more than one carboxymethyl group per anhydroglucose unit is necessary to produce aggregates which do not deteriorate after one month of alternate wetting and drying of the soil.

Certain water-soluble, polymeric electrolytes of high molecular weight which are markedly resistant to microbial decomposition have since 1952 been commercially available for use in the amelioration of poor soil structure. Some 61 polymers with soil aggregate stabilizing properties are described by Mowry and Hedrick (1953a, b) in the Monsanto Chemical Company patents. These compounds are characterized as follows:

"The various polyelectrolytes . . . are ethylenic polymers having numerous side chains distributed along a . . . linear carbon atom molecule. The side chains may be hydrocarbon groups . . . , sulfonic acid groups . . . , phosphoric acid . . . , heterocyclic nitrogen groups, aminoalkyl groups, alkoxy radicals (or derivatives thereof), the number of which groups and the relative proportions of hydrophilic and hydrophobic groups being such as to provide a water-soluble polymeric compound having substantially a large number of ionizable radicals."

For best results it was noted that molecular weights in excess of 10,000 were desirable and that with some polymers best effects were reached at 30,000 to 100,000. Cross-linked polymers were not as effective as linear polymers.

Three polymers have mostly been used: (1) hydrolyzed polyacrylonitrile (HPAN) supplied largely as a sodium polyacrylate; (2) a mixture of calcium hydroxide and a copolymer of vinyl acetate and the partial methyl ester of maleic acid (VAMA); and (3) a copolymer of isobutylene and the half ammonium salt-half amide of maleic acid (IBMA). Under a variety of trade names, these compounds are on the market in powder, flake, or liquid forms. They are usually formulated with inactive diluents for the reduction of hygroscopicity and for easier and more accurate application, thus reducing the amount of active material present.

2. *Factors Influencing Polymer Effectiveness*

Studies by Pearson and Jamison (1953) and others (Martin, 1953; Sherwood and Engibous, 1953) have shown that to be effective the polymers are best mixed with the soil at rates varying from 0.02 to 0.2 per cent. The soil should contain enough moisture for good workability. Gumming occurs if the soil is too wet. The soil should be remixed after

irrigation or precipitation if the soils are too dry. Liquid preparations are used on prepared seedbeds to ameliorate crusting or to control erosion.

Allison (1952), Demortier and Droeven (1953), Fuller *et al.* (1953), Hedrick and Mowry (1952), and numerous other investigators have demonstrated that the synthetic polyelectrolytes are effective in changing the structural properties of soils. The water stability of soil aggregates is greatly increased. As a consequence of greater aggregation, changes in porosity, water permeability, apparent density, the lower plastic limit, and workability ensue. All the polymers behave similarly. In general, greater aggregation has been obtained in the fine-textured

TABLE III

The Effect of Various Fertilizers on the Aggregate Stability of Paulding Clay When Treated with Soil Conditioners[1]

Fertilizer[2]	Rate/100 g. soil, g.	% aggregation (<0.25 mm.)			
		0.05% IBMA	0.1% HPAN	0.1% VAMA	None
None	—	98	86	94	24
KCl	0.02	93	65	94	
	0.20	88	64	95	
$KHSO_4$	0.02	96	88	93	
	0.20	81	85	94	
$(NH_4)_2SO_4$	0.02	96	91	96	
	0.20	95	87	95	
KNO_3	0.02	99	94	94	
	0.20	91	87	90	
NH_4NO_3	0.02	96	80	99	
	0.20	90	66	95	
KH_2PO_4	0.02	99	91	98	
	0.20	98	94	99	
Na_2HPO_4	0.02	94	84	96	
	0.20	96	92	96	

[1] Unpublished results obtained by M. B. Jones, Ohio State University.

[2] An average "starter solution" fertilizer formulation is 13–26–13 used at the rate of 4 or 5 pounds/50 gallons water. One-half pint of this is used per transplant. In these experiments, 70 ml. of solution of approximately the above concentration in terms of N, P_2O_5 and K_2O were applied to 200 g. of Paulding clay. This amount of solution will bring the air-dry soil up to approximately field capacity. The soil conditioners together with the fertilizer salts in solution were sprayed on the soil during mixing for uniform wetting. The soil was then placed in tumblers and allowed to stand overnight. It was then air dried and subjected to wet sieve aggregate analysis.

rather than in the coarse-textured soils (Martin *et al.*, 1952; Sherwood and Engibous, 1953).

The results of unpublished fertilizer compatibility studies with the synthetic polyelectrolytes made by M. B. Jones at Ohio State University are illustrated in Table III. These data and others (Martin, 1953) indicate that HPAN is influenced more by fertilizer than either VAMA or IBMA but that the magnitude of the effect is generally small. Field trials in which HPAN and VAMA were used with ammonium nitrate, ammonium sulfate, superphosphate, and potassium chloride showed no measurable differences in levels of aggregation attained.

3. Persistence in Soil

Field and laboratory tests indicate that the synthetic polymers are markedly resistant to microbial decomposition, although aggregate deterioration from cultivation, freezing and thawing, and other natural causes is indicated (Hedrick and Mowry, 1952; Martin, 1953). Tests with carbon^{14}-labeled HPAN and VAMA substantiated these observations as to the durability of the polymers (Martin, 1953). Brookston silty clay loam and Hoytville clay were incubated 130 days at 27° C. with continuous aeration and at field moisture except for freezing and drying cycles. Radioactive carbon dioxide equivalent to 2.7 per cent of the added HPAN and 0.2 per cent of the added VAMA was produced as a result of microbial decomposition. The addition of 1 per cent ryegrass increased the decomposition of the VAMA to 0.3 per cent. Comparable conclusions were reached from studies in Arizona (Fuller and Gairaud, 1954).

4. Comparison with Natural Organic Binding Substances

As noted above, the chief differences between the natural and the synthetic polymers (VAMA, HPAN, and possibly IBMA) is that the aggregating substances produced through microbial activity are much more subject to decomposition. It may take up to 2 to 5 per cent organic residue to produce the same level of aggregation obtained with 0.05 per cent IBMA or VAMA, and the aggregating effect of the former will deteriorate much more quickly. One should not overlook the fact, however, that the modification of soil structure affected by organic residues is not their only function, and the synthetic conditioners are not likely to replace the organics in management procedures but may be used in addition to or with them.

Recent tests were made by Martin and Aldrich (1955) at the University of California Citrus Experiment Station, Riverside, to obtain some direct comparisons of the binding action of certain natural and

synthetic materials. Briefly, VAMA, two dextrans from soil bacteria, IBMA, fructosan from *Bacillus subtilis*, and mesquite gum exerted the greatest initial binding effect; carboxymethyl cellulose and pectin exerted an intermediate effect; and ammonium alginate, arabogalactan (larchwood gum), and ammonium lignin sulfonate produced very little binding action. On the basis of the pipet method used for estimating soil aggregation in these studies, it appears that some of the microbial substances are initially just as effective as the better synthetic materials.

Slater and Rodriguez (1954) found that the stability of aggregates determined by wet sieving did not account for differences in structural quality between naturally stable and conditioner-stabilized Christiana silt loam. The two soils were equally resistant to slaking, but penetration and seed germination were better in the treated soil. It was suggested that the consistency of water-stable aggregates may be more important than their size.

5. *Effect on Plant Growth*

An advantage of the microbially resistant synthetic polymers over the natural soil conditioner substances is that they can be used as research tools to elucidate the importance of soil structure in plant response studies without the introduction of fertility factors, and at levels of application such that they make up a minute or insignificant part of the soil mass. It is now well established that the use of the synthetics on some soils for structural improvement has effected significant improvement in plant growth and yield, whereas in other soils yield increases have not occurred even though striking differences in aggregate stability have been brought about (Allison, 1952; Fuller *et al.*, 1952; Martin, 1953; Martin *et al.*, 1953; Pearson and Jamison, 1953). Root crops often improve in quality and come out of the ground cleaner following conditioner treatment of the soil.

Decreased plant growth in a soil containing appreciable exchangeable sodium could be caused by poor soil structure, the sodium ion, or both. Use of a soil conditioner that aggregates the soil in the presence of exchangeable sodium offers a means of better evaluating the two effects. A study of this type (Martin and Jones, 1954) indicated that up to 75 per cent of reduced plant growth at certain soil sodium percentages could be ascribed to the dispersing action of the sodium ion.

Very striking yield differences have occurred where early spring drainage has been improved or surface crusts ameliorated by conditioner treatment (see Table IV). Stands of direct seeded tomatoes were increased from 2150 to 3640 plants per acre from treatment of Paulding

TABLE IV

The Effect of 0.05% Surface Applications of Soil-Aggregating Chemicals on the Rapidity of Corn Emergence and Early Growth of Corn. Miami Silt Loam. Columbus. 1953[1]

Soil-aggregating chemical	Sept. 2	Sept. 4	Sept. 11	Avg. wt. per plant, g.	Avg. height per plant, cm.
None	1.6	4.4	6.0	5.6	30.3
IBMA	8.0	9.6	9.6	9.0	43.3
HPAN	8.6	9.4	9.4	10.0	41.6
CMC[2]	4.3	7.3	7.4	11.9	38.7
L.S.D. (0.05 level)	—	—	1.3	3.2	6.0

[1] Unpublished data by De Ment. Application rates calculated for a ½-inch soil depth. The experimental area was disked and cultimulched. Ten corn seed were planted per pot followed by liquid applications of soil-aggregating chemicals, and then hand irrigated with a water applicator which produced large droplets. An intense rain fell 2 days later. Corn planted on August 26. Plant heights and weights were taken 42 days later.

[2] Carboxymethyl cellulose 120 H.

clay with 0.15 per cent VAMA to a depth of 4 to 6 inches. Seed germinated but seedlings did not survive the waterlogged condition of untreated soils during periods of spring rains. Yields were increased from 9 to 22 tons per acre (Martin, 1953). It was noted in this experiment and others (Martin *et al.*, 1952; Swanson, 1953) that crops often not only get off to a better start in polymer-treated soils but tend to mature more quickly. The latter observation merits further research endeavor.

One way that has been found to reduce rates of application of the synthetic polymers to economical levels is to treat only the top half inch of soil for the reduction of surface crusting (Sherwood and Engibous, 1953). IBMA, HPAN, and carboxymethyl cellulose in solution at 0.2 to 0.4 per cent concentration, sprayed or sprinkled in a band treatment or put out as a jet stream over the row, have proved successful in this respect. The application rates required for improved emergence under these conditions range from about 30 pounds per acre for complete surface coverage, 2 to 5 pounds for band treatments, to a approximately 1 pound for the jet stream procedure. These rates are low enough to be of practical significance.

A further implication of crust reduction from polymer treatment is that more water infiltrates to the rhizosphere to meet crop moisture requirements. Growth differences in crust control experiments can in part be attributed to such moisture differences. Increase in rhizosphere moisture infiltration is undoubtedly more important to crop production

than changes in the moisture capacities or in available moisture, which are only slightly influenced by polymer treatment (Hedrick and Mowry, 1952; Peters *et al.*, 1953; Sherwood and Engibous, 1953).

A number of studies have suggested that the soil conditioners may, under some conditions, influence the uptake of nutrients by plants partly as a result of increased microbiological activity, and possibly through increased growth response to fertilizers (Fuller *et al.*, 1953; Fuller and Gairaud, 1954; Martin, 1953). MacIntyre *et al.* (1954) observed that soil treatment with HPAN, which contains sodium, tended to increase sodium absorption by plants and decrease absorption of calcium and magnesium. Studies by Martin and Jones (1954) indicated that, although plant growth was markedly improved in some tests, soil treatment with VAMA did not influence nutrient absorption by lettuce and radish plants. Sodium absorption by Lovell peach seedlings, however, tended to be reduced. In field tests at Ohio (Martin, 1953), plant tissue analyses in general indicated little influence of the polymers on nutrient ion uptake, even when they were applied directly with commercial fertilizers.

6. *Effect on Microbial Activity*

Microbiological activity appears to be increased in some soils by improvement in aggregation effected by the synthetic polymers. The "aeration factor" of Quastel and Webley (1947), based on the Warburg technique, which is essentially a measure of the oxygen demand of the soil population, is increased by polyelectrolyte treatment, as is the evolution of carbon dioxide (Fuller and Gairaud, 1954). As noted earlier, the increased evolution of carbon dioxide is not caused by the metabolic degradation of the applied polymers. Fuller and Gairaud also found that crop residues added to conditioner-treated soils decomposed more quickly. Nitrification rates (Sherwood and Engibous, 1953) and nodulation of alfalfa (Hely and Bonnier, 1954) have been reported to increase following conditioner applications to the soil.

VII. Mechanism of Soil-Binding Action by Organic Substances

The mechanism by which organic substances bind soil particles is of interest though still in the theoretical stage. Sideri (1936) and Myers (1937) demonstrated a direct binding action of clay particles by polar organic compounds. Kroth and Page (1947) concluded that polar compounds form physicochemical bonds with the surface-active clays which prevent breakdown of the aggregate on wetting. The superiority of polar substances produced through the decay of fresh organic materials was stressed.

Geoghegan (1950) observed that the aggregating effect of several bacterial levans varied with the molecular weight, that is, the larger the molecule, the greater the binding action. It was suggested that hydrogen bonding may be the mechanism by which polysaccharides bind soils. In this type of bonding, the hydroxyl hydrogen would be attracted to the oxygen atom at the exchangeable base sites on the clay as well as to the oxygen atom of the hydroxyl group in the polysaccharide. Deamination, esterification, and acetylation studies of humus extracts and of some proteins and polyuronides (Swaby, 1950) suggested that NH_2, COOH, and OH groups might all be involved in polar linkage between organic and inorganic colloids. The studies with humus extracts indicated that alcoholic, phenolic, and possibly amino groups were more important than carboxyl groups.

Ruehrwein and Ward (1952) believed that in order to bind soil particles the organic molecules must be long enough to bridge the gap between soil particles. It was postulated that the polymer molecules (VAMA, HPAN, and IBMA) were long enough to bridge this gap and that they were strongly adsorbed at the "anchor points" on the clay, probably by anion exchange. The chain length theory is supported by the findings of Geoghegan (1950), who noted a relationship between molecular weight and binding action of a series of bacterial levans. The molecular weight of dextrans from the *Leuconostoc* group of organisms is thought to be about 4,000,000, whereas that of arabogalactan from larchwood has been estimated to be 2200 (Whistler and Smart, 1953). In recent studies by Martin and Aldrich (1955) the binding action of *Leuconostoc* dextran was very marked, whereas arabogalactan exerted little or no binding action. This observation is also in harmony with the chain length theory.

Besides the length of the chain, the shape of the active molecule and the spacing of active sites could also influence binding action. If the molecule contains numerous long side chains or is tightly coiled, the clay particles may be kept from active binding sites. If active sites on the organic molecule coincide with active sites on the clay particle, binding may be more stable than if sites do not coincide.

Peterson (1948) proposed a scheme for calcium linkage between uronide particles and uronide and clay particles. Such a linkage can be illustrated as follows:

-Si-O-Ca-OOC-R-COO-Ca-OOC-R-COO-Ca-O-Si-

It was suggested that this type of linkage may be active in the formation of natural soil aggregates by polyuronides in the soil organic matter and root hairs.

With respect to the synthetic polymers, Michaels and Lambe (1953) hypothesized that the binding action of nonionic and anionic water-soluble polymers is caused by adsorption via ester formation or hydrogen bonding of hydroxyl or amide groups on the solid surfaces, each polymer chain adsorbing on or bridging between more than one solid particle. It is believed that the presence of ionic groups in the compounds is necessary only for flexible-chain compounds, and serves only to extend chains, thus preventing intramolecular polar group association and permitting interparticle bridging.

The exact mechanism of binding of soil particles by organic materials remains to be further clarified. It appears likely, however, that different mechanisms are involved with different types of organic binding substances. It should further be emphasized, as was pointed out in the first section, that adsorbed organic molecules may exert an important influence on clay particles other than a direct binding or linking together of clays by the organic molecule.

VIII. Influence of Exchangeable Cations on Aggregation

1. *Calcium versus Hydrogen*

It has been generally accepted that high calcium saturation of the soil colloids contributes to the formation of stable aggregates. Various investigations, however, suggest that the effect of calcium is either indirect or may not be as important as is commonly believed. Baver (1936) and Kappen (1931) found that replacing soil-exchangeable calcium with hydrogen or hydrogen with calcium did not affect aggregation of a chernozem soil. Baver made a correlation study of the degree of calcium saturation of soils and aggregation. No correlation was found. Peel (1937) added lime to Cecil clay under field conditions and noted that the lime tended slightly to reduce soil aggregation. Robinson and Page (1950) treated Brookston clay loam with hydrogen peroxide to destroy the organic matter and then saturated different portions with calcium, hydrogen, or sodium. Wet sieve analysis indicated that hydrogen was more effective in aggregate stabilization than was calcium.

Several investigators have suggested that calcium may influence aggregation indirectly through its effect on organic matter or microbial activity (Baver, 1935; Metzger and Hide, 1938). In this connection, a study by Aldrich (1949) is of interest. It was found that soil acidification in the field by sulfur additions did not affect flocculation of the soil but when the pH was reduced to approximately 4 or below, aggregation decreased. At this point, numbers of bacteria and actinomycetes were reduced to low levels and numbers of fungi were not materially in-

creased. Uronic carbon analyses showed reduced amounts at the low pH levels. It was suggested that decreased aggregation at the high acidity level was associated with a decrease in microbial activity with a corresponding decrease in the production of soil-binding substances.

2. *Exchangeable Cations in General*

In a recent study (Aldrich and Martin, 1954) the influence on soil aggregation of a wide variety of exchangeable cation ratios with and without the addition of fresh organic residues was determined. Exchangeable magnesium was varied from 2 to 80 per cent, potassium from 2 to 60 per cent, sodium from 0 to 60 per cent, and calcium-hydrogen from 70 per cent hydrogen saturated through base saturation to 5 per cent excess lime. The following results were noted: Increasing magnesium exerted no effect an aggregation; high exchangeable potassium only slightly reduced aggregation in one soil but appreciably reduced it in another; increasing sodium greatly reduced aggregation, whereas increasing hydrogen had no influence; an excess of free lime reduced aggregation; and the organic matter additions increased aggregation regardless of the exchangeable cation status of the soil. Increased aggregation, following organic matter additions, was least in the high-sodium soils.

Microbial activity was high in all the soils receiving organic residues. In the most acid soils, bacteria and actinomycetes were greatly reduced in numbers but fungus numbers were greatly increased. This further indicates that the fungi are as effective as the bacteria and actinomycetes in producing soil-binding substances during the decomposition of complex organic residues in the soil. Sodium increased microbial numbers but decreased aggregation. This cation disperses certain organic binding substances as well as the soil particles. The dispersion of organic substances could make them more susceptible to attack by soil organisms, thus explaining the increase in microbial numbers in the high-sodium soils.

The detrimental effect of sodium on soil structure is well known (Richards *et al.*, 1954). Soils containing a high percentage of sodium are usually referred to as alkali soils. De Sigmond (1928) and Magistad (1945) have suggested that exchangeable sodium and potassium be considered as additive in defining alkali soils, but there is evidence that potassium does not adversely affect soil physical properties as does sodium or to the same degree as sodium (Richards *et al.*, 1954). In the study by Aldrich and Martin (1954), aggregate analysis of the $<50\text{-}\mu$ units in Hanford soil indicated that potassium exerted a marked dispersing action on this soil. Casual examination of the high-potassium and

high-sodium soils, however, indicated different physical characteristics. The sodium soils were exceedingly difficult to crumble when dry, whereas the potassium soils crumbled with relative ease. Measurement of the 2-μ particles in the two soils revealed that the clay particles of the potassium soils were essentially completely aggregated, whereas those in the sodium soils were 30 per cent dispersed.

3. *Effect on Natural and Synthetic Soil Conditioner Substances*

Geoghegan (1950) reported that two polyuronides, pectin and alginic acid, exerted little effect in sodium and calcium soils but had a marked aggregating effect in hydrogen soils. This observation agrees with the results of Martin and Aldrich (1955). In this study, the effect of exchangeable cations on the binding action of a variety of natural polysaccharides and of carboxymethyl cellulose appeared to be directly related to the concentration of carboxyl groups in the material. Taking a neutral soil saturated largely with calcium as a starting point, as the concentration of uronic units in the polysaccharide increased, the binding action increased with increasing exchangeable hydrogen and decreased with increasing sodium or potassium. Straight sugar group polysaccharides tended to produce greater aggregation than the polyuronides and were not as readily influenced by changes in exchangeable cations. Typical results of this study are illustrated in Table V.

The influence of exchangeable hydrogen on the binding action of polyuronides may be explained on the basis of its effect on hydrogen bonding. Under neutral or alkaline conditions, an alcoholic hydrogen atom could be attracted by a carboxylic acid oxygen in the same molecule or in another molecule of the same material. This would reduce its attraction to the clay particles. Under acid conditions, on the other hand, hydrogen would be strongly held by the carboxylic acid oxygen. This would reduce its coordinate bond attraction for the alcoholic hydrogen atom, and the attractive force of the latter for the clay particle would therefore be increased.

Further, under alkaline conditions, the cations associated with the carboxylic acid groups of the polysaccharides and with the clay particles would tend to form hydroxides with the hydroxyl ions in solution. The negatively charged clay and organic particles thus formed would tend to repel each other. In acid systems, the polyuronide particles would exist largely in the unionized form, and therefore the clay and polyuronide particles would not repel each other.

These observations suggest that hydrogen bonding through the alcoholic group of polysaccharide materials is more important than are uronic acid groups in their binding action on soil particles, although

TABLE V

Effect of Different Exchangeable Cation Percentages on Aggregating Influence of Various Soil Conditioner Substances on Yolo Loam[1]

Exchangeable cation percentages	Con-trol	VAMA 0.2%	IBMA 0.1%	Carboxy-methyl cellulose 120H 0.2%	Dextran from a soil bacterium 0.3%	Mesquite gum 0.3%	Dextran from *Leuconostoc dextranicum* 0.3%
	Percentage aggregation of <50-μ particles						
2% Mg	34	66	66	42	52	52	73
20% Mg	33	70	66	45	65	52	77
80% Mg	33	75	62	47	61	54	75
10% K	34	70	62	42	66	51	75
30% K	34	71	49	23	62	44	76
60% K	34	75	41	16	58	42	79
0% Na	34	70	62	42	66	51	75
10% Na	32	74	52	16	66	42	83
30% Na	19	75	39	4	59	25	86
58% H	34	68	44	83	66	54	75
16% H	33	71	65	66	64	52	75
0% H	34	70	62	42	66	51	75
5% $CaCO_3$	29	63	61	43	56	45	65

[1] Martin and Aldrich (1955).

the uronic acid group may be of greater importance with respect to persistence in the soil.

The synthetic soil conditioners, VAMA and HPAN, are apparently not as readily influenced by exchangeable sodium as are some of the polyuronides and soil humus (Allison, 1952).

IX. Water Penetration under Prolonged Submergence

Water spreading for underground storage is practiced in certain western areas (Michaelson and Muckel, 1937). For this purpose excess water during periods of high runoff is turned into ponds in spreading grounds. When the water is first turned into the ponds, percolation is relatively rapid but soon drops off until the ponds virtually seal up. Allison (1947) and McCalla (1951) have demonstrated that the sealing action is caused by microbial activity. It is believed that the soil pores become clogged with products of growth. If the soil is dried and mixed, however, aggregation greatly increases. It appears that the same

materials that exert a favorable effect on soil structure under one set of conditions may exert an unfavorable effect under other conditions, and emphasizes the importance of factors other than the presence of binding substances in favorable structure formation in soils.

X. Summary and Conclusions

Microorganisms influence the physical properties of the soil by aiding in the process of water-stable aggregate formation. The influence may be direct or indirect, the latter acting through the compounds produced during decomposition. The favorable effect of microbes is contingent upon the decomposition of organic residues in the soil. During the decomposition process, substances synthesized by the organisms and products of decomposition undergo chemical and physical interactions with the soil particles which may increase aggregate stability. During periods of intense microbial activity, the cells and filaments of the organisms themselves may mechanically bind soil particles together. The soil-binding substances produced through microbial activity are slowly or quickly destroyed by subsequent microbial action. In order to maintain aggregate stability at a high level, a continuous supply or periodic additions of organic residues are necessary.

Microbial species and different types of organic residues vary in their soil aggregate stability effects. Some fungi or bacteria are very effective, whereas others have little influence. In general, complex organic residues containing relatively large amounts of easily decomposable constituents bring about greater aggregation than substances which are relatively resistant to decomposition. Low or moderate temperatures and moisture conditions are more conducive to stable aggregate formation than are higher temperatures and excessive moisture. Exchangeable cations in the soil influence soil aggregation.

Polysaccharides synthesized by soil organisms are effective soil-binding substances but other organic compounds are undoubtedly active. More work is needed to determine the nature of the active substances produced through microbial decomposition of organic residues.

The effects of organic substances on soil binding appear to be associated with OH, NH_2, and COOH groups, and with the length and special characteristics of the molecules. Hydrogen bonding through the alcoholic hydrogen may be the mechanism by which polysaccharides bind soil particles. Different types of organic compounds may bind soil particles through different mechanisms. More work is needed further to elucidate this aspect of soil aggregate formation.

Some of the synthetic polymeric soil conditioners currently available for use are markedly resistant to decomposition and can, when

properly applied, effect marked improvement in the physical properties of the soil. They are not likely to replace organic matter in soil management procedures but can be an important supplement thereto. One important advantage of certain synthetics is that they can be used as a research tool to elucidate the importance of soil structure without introducing fertility factors, and at exceedingly low concentrations.

The action of organic compounds in affecting aggregation may be very complex and at best is little understood. Many have postulated that soil particles are held together in aggregates by the organic compounds. There is, however, considerable evidence that another important role of these compounds may be in modifying the expression of cohesive forces between clay particles through adsorption on the surfaces of the clay. Thus, active organic materials may be thought of as acting both to hold soil particles together and in other cases to hold the clay particles apart. The exact mechanisms involved in formation and stabilization of soil aggregates need to be studied intensively if a full understanding of this important soil characteristic is to be obtained.

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Recent Changes in Swedish Crop Production

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CONTENTS

I. Swedish Crop Production—Background

1. Sweden—Location, Climate, and Soils

Sweden is located far to the north, between 55° and 69° N. The country has a length of about 1000 miles from south to north. With its widest part stretching over about 300 miles from east to west between 10° and 24° E., Sweden is a rather large country, particularly with regard to length. With its location far to the north this means that there are great variations in climatic conditions. There are correspondingly great variations in the types of agriculture existing in different parts of the country. Typical of the climate in the northern part are very short summers with extremely long days, and long winters with a

heavy snow cover. Characteristic of the climate in the middle and southern parts of the country are short summers with long days and rather cold and windy winters. In the southernmost provinces in Sweden the snow cover does not usually stay on the ground very long. The cold winds can therefore be hard on the overwintering crops. Conditions like the ones just mentioned require an extremely good winter hardiness in the overwintering plants.

Under the conditions indicated above, there must exist marked differences between temperatures in different parts of the country, ranging from a mean annual temperature of 7° C. in the southernmost parts of the country down to —3° C. in the northernmost parts. Although these temperatures are low, they are still higher than in most countries at the same latitude. This is due to the Gulf Stream, which brings warm winds from the Atlantic across the country. These winds warm up mainly the areas in the south. The mountain ranges on the border between Norway and Sweden prevent the winds from giving northern Sweden a more genial climate. Differences in climate are, however, not due merely to the influence of the Gulf Stream. Sweden has a varying topography, and the elevation above sea level has a definite influence on the climate in local areas. Typical plains are found in the extreme south; across the central part there are lowlands bordering on the great lakes Vänern, Vättern, Hjälmaren, and Mälaren, and along the coast line and the rivers there are coastal plains and valleys. These plains, lowlands, and valleys are, however, broken off by mountain areas and by forested uplands, mixed with small farmland areas. Mountain areas are found primarily in the northern parts of the country, but the forested uplands are found in most parts of the country except in the extreme south and along the coast lines. In such areas the climate is more severe than in the lowlands and the plains, even though they are located at the same latitude. Consequently there are different climatic conditions for crop production all over the country. This must be borne in mind when crop production in different districts of the country is discussed below.

The danger of night frosts during spring and fall confronts the crop producer with another problem. In southern Sweden late spring frosts are most likely to cause crop damage, and especially to those which are now at their northern growing limit. These crops are sensitive to a night frost after they have emerged. In northern Sweden, on the contrary, the fall frosts are most dangerous, as they often appear before the cereal crops are ripe. In the upland areas in different parts of Sweden these night frosts can occur during every month but July. It occasionally happens that not even the month of July is free of night frosts. But on

an average it can safely be said that the length of the growing periods, i.e., periods with a mean temperature of above 3° C., is 250 days in south Sweden, 200 days in the areas just north of Stockholm, and 150 days in northernmost Sweden. One might be tempted to think that the short growing season in northern Sweden would make it impossible to cultivate anything but grasses and clovers in those areas. However, long days may alter the picture. There are, for example, 340 sunshine hours in the northern coastal area, as against 250 sunshine hours in the southwestern area.

The average rainfall in Sweden is moderate, in the cultivated areas varying between 400 and 1000 mm. There are of course some differences between different districts. These are particularly marked in comparing the western and eastern parts of south and middle Sweden. In the western parts there is a heavier rainfall than in the eastern. This influences the choice of crops, meaning that grasses and clovers as well as oats are more common in the western parts than in the eastern. Dry spells are rather common in the eastern parts during late spring and early summer. Such dry spells can cause poor stands of spring-sown crops. In the areas where such dry spells are known to appear, fall-sown crops are used quite extensively in order to eliminate the disadvantage of spring sowing. They will have a better chance than have spring-sown crops of coming through the dry periods during the early part of the growing season. A typical feature of the distribution per year of the precipitation in Sweden is the fact that the spring and the early summer generally are quite dry, while the fall is rather wet. Such a distribution gives neither an ideal growing season nor a good harvest season.

Apart from depending, to a large extent, on the climate, crop production is highly dependent on the soil. There is a great variation in soils. Typical are fertile clays, good and poor sandy soils, peat soils rich in lime as well as in nitrogen, and organic soils poor in nutrients. The great diversity of soils means that soil drainage, soil management, and use of fertilizers must be closely studied. This is actually being done in a very satisfactory way. The questions discussed above were treated in detail by Osvald (1952).

2. The Present Pattern of Crop Production—Background

The old pattern of crop production, forming the background to those now prevailing, illustrates in many ways what kinds of crops are adapted to the climate and soils of Sweden. A good idea of the development can be found in the crop rotations used in different periods of Swedish agriculture. Crop rotations were introduced about 250 years

ago and have since undergone remarkable changes. Before their introduction there were no special plans for crop production. The meadows were broken up and seeded with cereals during a period of years, i.e., as long as these newly broken lands were able to produce a crop. Alternatively, a forested area was cut clean, with the trees left on the ground to be dried and burned, so that the area after cultivation could be seeded with cereals or turnips. As in the case of the meadows these newly cleared areas of forest land were used for the production of crops as long as possible.

When the land obtained from the meadows or from the forests did not produce enough, it was left without care, resulting in an abundant growth of volunteer plants, mostly weeds. As time elapsed this weedy land was again plowed up and seeded with cereals. It was then discovered that on land where plants with other requirements for nutrients and with a root system different from that of the cereals had been grown, good cereal yields were obtained. They were markedly better than the yields on land where cereals had been grown continuously. Of course this was due, to some extent, to the plowing under of the growing plants, their root growth, and the humus enrichment which they accomplished. There is a similarity between the effect of resting this open land with resultant volunteer growth of plants and the effect of the meadows when they were first broken up. This similarity soon taught the Swedish farmers how to increase production through the use of rotation systems in which fallow and cereals were the main components or in which temporary leys and cereals alternated. All this was about 250 years ago. In these rotations the fallow alternated with two, three, or four years of cereals.

The use of cereals in alternation with established but temporary clover and grass leys followed. In these rotations cereals were grown for three to four years and temporary leys for four to ten years. The temporary ley was plowed up, fallowed, and again seeded to cereals. This type of rotation became unsatisfactory as the requirements for high yields per hectare increased. The introduction of balanced crop rotations was therefore of great importance in the development of Swedish agriculture. These rotations were greatly influenced by the Norfolk rotational system: wheat, root crops, spring-sown cereal, and temporary ley. But the Swedish crop rotations did not, as a rule, develop into a four-year rotation system similar to the old Norfolk system. Instead they developed into seven-, eight-, nine-, or ten-year rotations. Typically, the crops were arranged so as to fit both the principles laid down in the Norfolk rotation and the varying local requirements of crop production in Sweden. Numerous types of balanced crop rotations have

appeared. An example of earlier and less effective ones is: black fallow, winter wheat or winter rye, three years of a temporary ley, winter wheat or winter rye, root crops, spring-sown cereal. This rotation appeared to be poor because the temporary ley was undersown in a fall-sown cereal and was allowed to remain for a period of three years. The root crops had a poor place in the rotation, and the second winter wheat crop had also a poor place, as it followed after the third-year ley. In this the stand is generally poor and most often consists of grasses and weeds. A great improvement was a balanced crop rotation of the following type: black fallow, winter wheat or winter rye, root crops, barley, two years of a temporary ley, winter wheat or winter rye, oats. This rotation is not, however, a very intensive one; it is rather an average type of a good balanced crop rotation. As the years went by the balanced crop rotations became more effective and more adapted to the local conditions in different parts of the country. This, together with improvements in the yielding capacity of the cultivated plants through plant breeding, increased yield per hectare as a result of better soil drainage, extended use of fertilizers, better soil management, and better care for the crops during the entire growing season, meant a remarkable development of Swedish crop production during the last 75 to 80 years. This trend, it seems, became more obvious during the last two decades than at any earlier time.

3. *Developments during the Last Two Decades*

The developments during the last two decades are characterized by changes resulting from the farmers' lack of understanding of the value of biological considerations as against their appreciation of technical and economic considerations. There has been an unwillingness to give proper weight to some of the biological principles, the earlier recognition of which meant so much to the improvement in crop rotations and to the rapid increase in Swedish crop production during the latter part of the 19th and the early part of the 20th centuries. Instead, technical and economic measures, which are so important in the efficient operation of the farms in present-day farming, are overemphasized. This change in the attitude of the farmers has resulted in the fact that crops requiring a great amount of labor have decreased in acreage. A good example of this is the development of root crop cultivation. To a high extent crops are now selected on the basis of the degree of mechanization that they allow. There are now about 107,000 tractors in the country, whereas there were only about 15,000 in 1939. The combine harvesters have increased from about 100 in 1939 to about 13,000 in 1954.

The recent developments have also been affected by the prices fixed for different crop products. For instance, when the Swedish Government wanted an increased production of oil crops during World War II and the years immediately following, they set the prices on rapeseed, white mustard seed, and seed flax in such a way that increased growing of oil crops could be expected. The result was as desired: the acreage of oil crops increased rapidly up to 1951. Such a situation meant that the farmers did not pay much attention to the biological requirements of the plants. Oil crops, belonging to the same botanical family, were grown for one, two, or several years in succession on the same field. The continued use of the same crop on the same field meant new and increased attacks of parasites. With these followed diminishing yields, and during the last three years also a decline in acreage of the crops. During recent years the prices set for cereals have been such that the acreages of wheat and rye have increased. At the same time the acreage of leys and pastures has decreased. The latter was the result of a reduction in the number of cattle following the shift on many farms to farming without cattle. In 1939 there were approximately 3,000,000 head of cattle in Sweden. Of these 1,920,000 were milk cows. Now there are about 2,500,000, and 1,600,000, respectively. On the other hand, production per cow is now 3200 kg. milk as against a mere 2650 kg. in 1939. There is, in other words, no decrease in total milk production in the country, rather an increase. On one-tenth of the Swedish farms there are no cattle today.

This development means that there is at present a tendency to increase the acreages of cereals and to decrease the acreages of crops which, from the biological viewpoint, are suitable for alternation with the cereals, e.g., root crops, leys, and legumes. In Table I will be found some figures which illustrate the trends discussed here. It can be said that the almost one-hundred-year-old practice of using balanced crop rotations is gradually being replaced by a practice of an optional crop order. Such a development must be considered a step forward, as it requires from the Swedish farmers a better knowledge of the properties of the crops grown. A rotation system with a free order between crops has good possibilities for growing large areas of crops which for economic reasons, may be desired during certain periods, without lowering the future productive capacity of the land. But such a rotation system, if it is going to be effective, calls for farmers who know the resistance or the susceptibility of different crops to diseases or pests, the ability of the crops to compete with weeds, the requirements of the crops with regard to nutrition, temperature, and moisture, and the amount of labor needed for each crop. As all these factors must be considered in a

TABLE I

Acreages (Thousand Hectares) of Certain Crops in Sweden in Recent Years as Compared to the Acreage of the Same Crops during Earlier Periods

Years	Wheat	Rye	Barley	Oats	Peas, beans, and vetches	Fodder roots	Sugar beets	Potatoes	Oil crops	Temporary leys for hay	Fallow	Total cultivated lands	Natural grasslands
1876–80	68	366	232	621	53	11		153	—	675	414	2831	1906
1906–10	92	406	193	793	33	27	26	155	—	1159	409	3566	1421
1936–40	307	189	102	657	25	81	45	133	—	1379	253	3728	1127
1941–45	280	209	103	579	34	66	53	142	28	1325	194	3738	1000
1946	303	157	90	531	27	65	55	143	27	1348	205	3720	940
1947	292	115	100	529	26	61	48	142	43	1352	208	3722	940
1948	316	160	88	490	25	61	48	148	79	1319	182	3724	940
1949	307	135	86	502	28	54	49	135	142	1298	177	3727	940
1950	339	127	94	502	23	50	54	130	169	1275	172	3728	940
1951	328	98	110	500	24	46	54	131	190	1261	178	3730	940
1952	332	126	153	516	22	43	54	136	148	1225	175	3732	940
1953	391	135	190	506	23	40	51	137	78	1215	198	3733	940
1954	433	150	168	478	26	34	59	123	100	1174	183	3733	940

system of a free order between crops, adoption of such a system actually means a definite step forward in Swedish crop production. A free order of the crops makes possible far better adjustment to the needs for crop products inside and outside of Sweden than do balanced crop rotations. This is important now that Sweden is self-sufficient in food production and derives some revenue by exporting certain farm products.

II. Crops and Special Measures

1. *Wheat*

There have been great changes in the acreage of wheat in Sweden since the beginning of this century, as can be seen from Table I. During the period 1936 to 1940 about three times as much wheat was grown

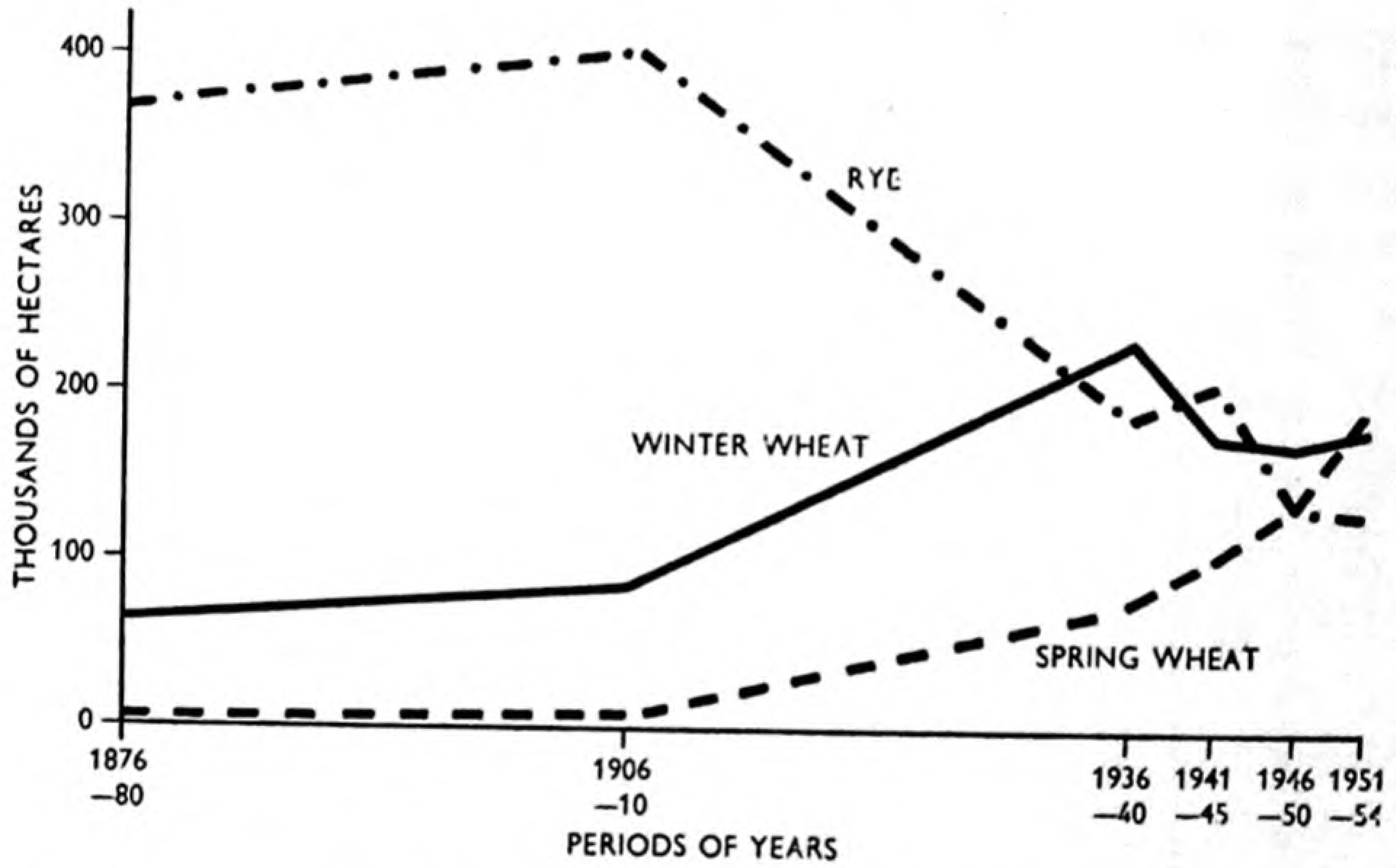

Fig. 1. Acreage of bread cereals during the period from 1876 to 1954.

annually as 30 years earlier. As can further be seen, wheat was steadily grown on about 300,000 hectares per year from the period just mentioned up to 1950, when the beginning of another increase in acreage can be noted. This increase has continued ever since. The reasons for this development can be found partly in the shift in the Swedish diet from rye bread to wheat bread. The figures in Table I clearly show a decreasing acreage of rye. Thus the rye acreage during the period 1936 to 1940 was only half of that during the period 1906 to 1910. But this is not the only reason. As will be seen later, additional reasons must be sought in the crop production figures.

The figures for wheat in Table I are the combined total acreages of winter wheat and spring wheat. The relationship between these two wheats is, however, not constant. It is characterized rather by a certain change from winter wheats to spring wheats (Fig. 1). It means, for

example, that during the period 1906 to 1910 there were 85,648 hectares winter wheat and 5931 hectares spring wheat; in 1936 to 1940 the figures were 231,297 and 75,644, respectively, and in 1953 they were 190,197 and 200,318. The yields from these acreages have been considerable during the last two decades. Thus the total yields of wheat per year were 672,812 tons during the period 1936 to 1940, 491,656 tons in 1941 to 1945 and 643,896 tons in 1946 to 1950. In 1951, 477,330 tons were harvested; in 1952, 782,290 tons; and in 1953, 996,160 tons. There has been recently therefore a substantial increase in total yield. The figures can, for example, be compared with those from the period 1906 to 1910, a mere 190,657 tons, or with the yields in the latter part of the 19th century, which varied between 90,000 and 100,000 tons. The yields per hectare show, even better than the total yield figures, the increase in production that has resulted from the adoption of newer practices. During the last two decades the yields of winter wheat per hectare for the country as a whole were 28 per cent higher than they had been during the period 1906 to 1910, and 50 per cent higher than during the period 1876 to 1880. For spring wheat the corresponding figures are 18 and 19 per cent, respectively.

The figures given above raise questions as to what are the changes in production practices and the achievements in crop production and crop breeding that are responsible for the results obtained. It should then be remembered that crop rotations and soil management and fertilizers were little understood in earlier days. Not until the period from the middle of the 19th century to the beginning of the 20th, when balanced crop rotations were first used, were these factors considered. Regular use of complete fertilizers according to definite plans for different crops dates back only two or three decades. The methods of using fertilizers are still being improved. The assignment of wheat to such a place in the rotation that it can take advantage of the fertility of the soil, develop well, and compete successfully with the weeds is not very much older. Soil drainage, in order to give conditions for good soil management, became an important factor in the production of wheat during the last two or three decades. Adding to this the increased use of high-quality seed and of seed disinfectants, the picture of those factors that are of importance in the production of wheat becomes even clearer. The value of high-quality seed is well known to the farmers producing wheat. Seed disinfectants are at present used by practically every farmer, as are chemicals against weeds, diseases, and insects. It is very difficult to find out the share each one of these production factors has had in the yield increase. Åkerman (1946) analyzed the reasons for the yield increase in wheat during the period from 1885 to

1935 and stated that the extended use of artificial fertilizer and the improvements in these production factors are responsible for about three-fifths of the yield increase per hectare. This statement seems to be correct also for present-day conditions. Still, production could not have reached the above-mentioned proportions if the plant breeders had not simultaneously produced new varieties to fit the requirements for an increasing productivity on the farms. It must therefore be strongly emphasized that it is plant breeding, together with the better production methods on the farms, that has made possible the successful development of wheat production. This combination has made it possible for Sweden to become self-sufficient in wheat, and furthermore has made it possible for her to export wheat in recent years. Åkerman (1946) further stated that two-fifths of the increase in wheat yields have arisen from the activities of the plant breeders. This may be correct, but it should be added that the improvements through breeding have been of great importance not only for yields but also in many other respects.

The winter wheats in Sweden at the time when plant breeding started were "land" wheats, i.e., indigenous types that had been grown for a number of years. Characteristically they had good winter hardiness and good baking quality but also a long, weak straw and a rather low yield per hectare. Their characters made them satisfactory for growing during periods when wheat was used in crop rotations where fertility was low and requirements for yield not very high. As soon as better rotations and better conditions for production became a reality, these types were no longer sufficient. It was under these conditions that the old land wheats were crossed with the SQUAREHEAD wheat from England. The aim was to obtain winter-hardy varieties with a stiff straw and a good yield. Such types became more and more desirable during the first 20 or 30 years of this century. The winter hardiness was to come from the "land" wheats, whereas the stiffness of straw and the increased yield were to come from SQUAREHEAD. The plant breeders were very successful in this work. Among the first results were EXTRA SQUAREHEAD II (in 1909), PANSAR I (in 1915), and THULE I (in 1914) from the Swedish Seed Association, Svalöf, and IDUNA (in 1911) and STANDARD (in 1921) from the Weibullsholm Plant Breeding Station, Landskrona. These varieties and the further improvements that followed at short intervals made it possible for the Swedish farmers to take advantage of crop rotations and good applications of manure and artificial fertilizers. The growing of wheat thus became more and more advantageous. From this followed an increase in acreage and a desire to use wheat in areas where the possibilities for overwintering seemed doubtful. The new varieties had good yielding capacity and a good

stiffness of straw from SQUAREHEAD but at the same time a weaker winter hardiness than was typical of the old "land" wheats. It then seemed logical to start a breeding program aimed at improvement in winter hardiness. Special attention has been given to this character both at Svalöf and at Weibullsholm. Artificial cold tests are used together with testing and selection in the field. The problem of winter hardiness is, however, a very complex one (Åkerman and Lindberg, 1927; Andersson, 1944). It is not only a question of cold tolerance; it is also one of resistance to heaving and drying in the spring, and to a number of diseases (*Fusarium*, *Typhula*, and others). The program has met with success. Examples of varieties used in present-day agriculture are AROS, ERGO II, and ERTUS from Weibullsholm, and ODIN from Svalöf. These varieties are grown in middle Sweden up to latitudes 61° N. An even hardier variety is VIRTUS, which can be grown up to 62° N. With great enthusiasm the work on improved winter hardiness is being continued by the plant breeders, and now also at the Institute of Plant Husbandry of the Agricultural College in Uppsala, where detailed studies of the various factors influencing winter hardiness are at present being carried out. The work with rye × wheat (*Triticale*) in Sweden also aims at a better winter hardiness in bread cereals of wheat type. So far no material from these crosses is available to farmers.

Better winter hardiness helped to bring still higher total yields of wheat; this meant less need for wheat imports than in earlier days. When the millers thus had to rely almost entirely on Swedish wheats, they required improved milling and baking qualities in these wheats. As a consequence both the breeders and the growers have been paying great attention to the production of wheats with high quality during the last 20 or 30 years. The breeding of new varieties in Sweden always takes into consideration milling and baking quality. Good quality can be obtained by crossing Swedish wheat varieties with the old "land" wheats or with foreign wheats of high quality, for example, Hungarian wheat. The new varieties of winter wheats, such as SKANDIA III and ODIN from Svalöf, and EROICA II and ERTUS from Weibullsholm, give good high-quality yields (4000 to 5000 kg. per hectare), have stiff straw, and good winter hardiness for the districts where they are intended to be grown.

These data on winter wheat show that the agronomic characteristics of this crop as well as the methods of growing it have been greatly improved. Nevertheless there is a considerable change-over to spring wheat, and at present winter and spring wheats are grown on about the same acreage. The reason for this is to be sought mainly in the better milling and baking quality which is, and has long been, typical of spring

wheat. In spite of the fact that the quality of the winter wheats has been improved, there is no doubt that the spring wheats have a better quality, mainly as a result of a higher protein content. As a consequence spring wheat started to increase in acreage when the production of wheat in the country reached the stage where quality became decisive. Such a development was promoted by the Government, whose price policy often favored spring wheat.

The interest in spring wheat brought with it also an interest in improving it. The old varieties were rather late, had weak straw, and low yields. In many ways the breeders have tried to improve these characters. They have probably been most successful in crossing winter and spring wheats so as to combine the yield and the stiffness of straw in the winter wheats with the quality of the spring wheats. By crossing available spring wheat varieties with early land wheats some further progress was made. One of the first good varieties was EXTRA KOLBEN II, which came from the Swedish Seed Association in Svalöf in 1926. Other varieties of importance were DIAMANT I and DIAMANT II, available in 1928 and 1938, both from Svalöf. They were bred mainly with the idea of getting an early spring wheat. As such they have been very good, and have been planted up to central Sweden. To a great extent the breeding work in recent times has been based on crosses between winter wheat and spring wheat. From such crosses originate PONDUS from Weibullsholm and ELLA from Svalöf. KÄRN II stands in between, as it originates from crosses between spring wheats and a wheat of alternating type. All are good yielding varieties but rather late. In spite of its lateness KÄRN II is grown very widely and has been of great importance. A new variety from Weibullsholm, SVENNO, is closely related to KÄRN II but also competing with it. SVENNO is earlier and has an even better straw stiffness than KÄRN II.

Both for winter and spring wheats there will arise new problems as a result of the large acreage of wheat and of the mechanization of Swedish farms. The large acreage brings with it danger of disease and insect attacks. Diseases caused by *Erysiphe, Fusarium, Ophiobolus, Cercosporella,* and others are well known. Breeding with special emphasis on resistance to parasites is needed, and farming practices inhibiting the development of parasites are imperative. The increased use of combines in Sweden, where weather conditions in late summer and fall are often poor for such a type of harvesting, calls for varieties that are not damaged by wet weather. Both delayed germination of the kernels and resistance to shattering are highly desirable. Characters like these are very valuable when a wheat field must be left for one or two weeks after combine ripeness before it can actually be combined. Detailed

studies of these characters in wheat and other cereal crops are under way at the Institute of Plant Husbandry of the Agricultural College in Uppsala.

2. *Rye*

It was pointed out in the discussion of wheat that rye had lost in acreage while wheat increased. According to the figures in Table I the present acreage of rye is not more than one-third of that at the beginning of this century. The shift from rye bread to wheat bread was given above as one explanation of this development. Other explanations could be sought in the difference in yields, stiffness of straw, germination in the field during the ripening period, and fitness for combining. All these factors have played an important role in the farmers' decision as to whether they should grow rye or wheat. In general the wheats have been better than rye in regard to the factors mentioned. As a result wheat has often replaced rye on the good lands and in the areas where the better winter hardiness of the rye is not a necessity for the growth of a winter cereal. This means that rye is today grown in the northern parts of the country, in those areas of middle and south Sweden where the climate is especially severe, and on the sandy soils or the peat soils where wheat does not give good results.

This development, together with the fact that rye is a cross-pollinated crop, has meant that the breeding work with rye did not reach the proportions of that with wheat. Breeding work has been carried out at the Swedish Seed Association in Svalöf and its branch stations and has given as results the variety KUNGS II, used to a high extent in south and middle Sweden, and the variety BJÖRN, used in northern Sweden. In recent years there has also come from Svalöf the tetraploid rye DUBBELSTÅL, which is being tested in comparison with the diploid ryes. A recent variety of rye for middle and south Sweden is AGRO II, produced at the Holmberg Plant Breeding Station in Norrköping. The German variety PETKUS II is also used.

Although rye production is at present rather low, it covers Sweden's present needs. In fact, there is some surplus for export or feed. The decrease in the acreage of rye since the beginning of the century is therefore no more than an adjustment to the conditions in crop production as these are shifting with the developments inside the country and abroad.

3. *Barley*

Barley in Sweden is mostly a fodder cereal; only about 10 per cent of the production is used for malt. The malting barleys are all of the two-rowed type, which is also the main type grown in south Sweden

and parts of middle Sweden. Six-rowed barleys are found in northern Sweden and in those areas of south and middle Sweden where an early-maturing type is desired (Fig. 2). The six-rowed barleys in northern Sweden are to a certain extent used for bread baking, i.e., for the thin hard bread used in these areas of the country. The figures in Table I show a decrease in the barley acreage of more than one-half from the beginning of this century up to 1950, but this decrease does not really

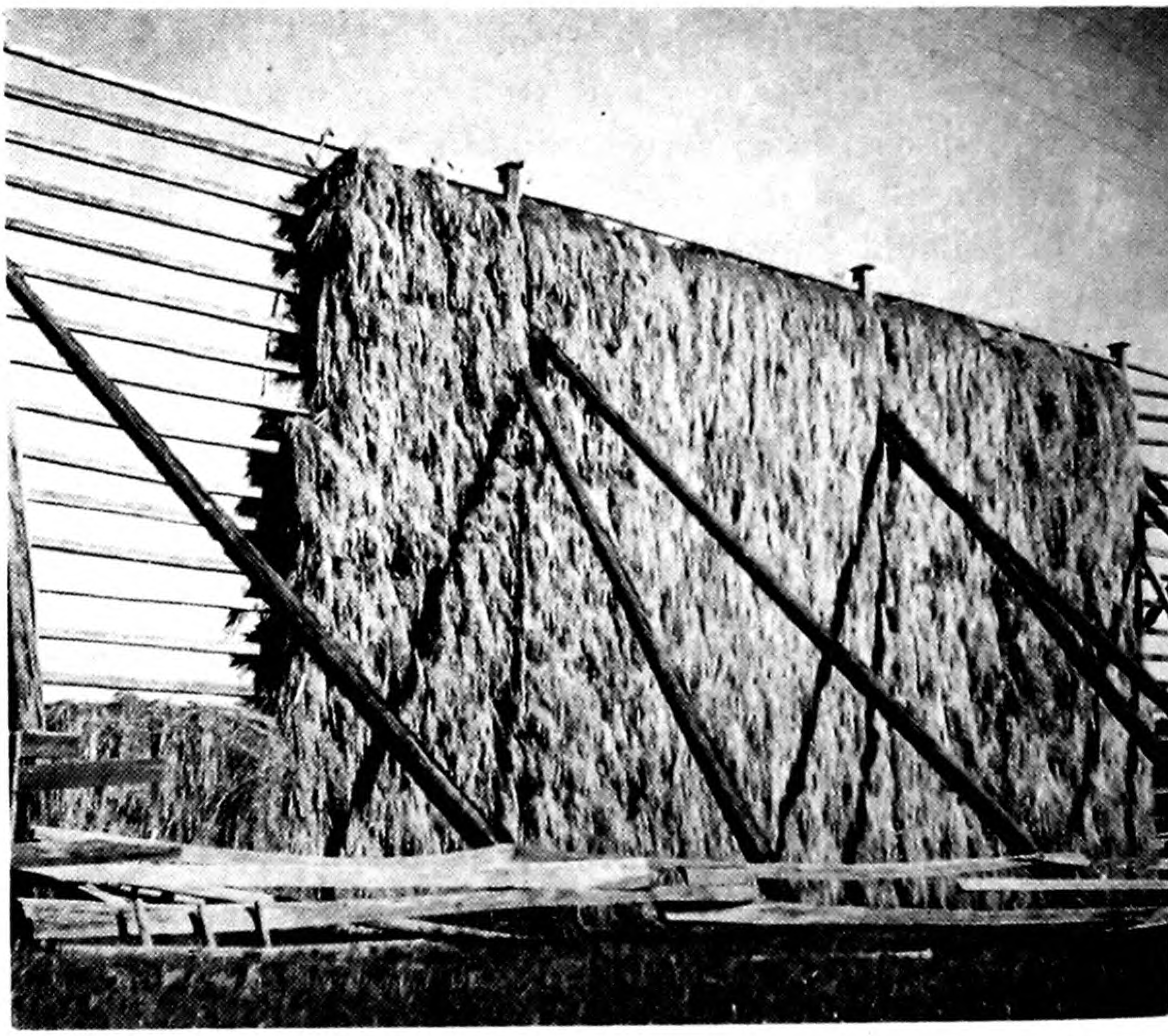

FIG. 2. Twenty years ago big racks (storhässjor) like this were used for drying cereal. It was hung on these racks facing the prevailing winds. Now these racks are not common. Near Näsåker in northern Sweden, 1949.

mean that barley was given up by the farmers. It was instead grown in mixtures with oats for feed. Such mixtures have been used extensively in recent years, as is illustrated in Fig. 3. For a number of years they have been giving better yields than barley alone because one of the two cereals always can be expected to have a good year and to develop well. When farming without cattle became of interest, a number of farmers again turned to barley alone as it was easier to sell than the mixed product. This is one of the reasons why the barley acreage in Table I has again increased since 1950.

When the plant breeders a few years ago released two-rowed varie-

ties with very stiff straw, two-rowed barley became particularly suited to combine harvesting. These new varieties can be left on the field for two or three weeks after they are ready for combining without suffering from the weather. The possibility of combining the two-rowed barleys also made them more popular than before. Swedish barleys are rough-awned and not nice to handle if they are cut with a binder, dried in the field, and brought to a stationary thresher. The situation is different when combines can be used. Another advantage of the stiff straw in the new two-rowed varieties is the possibility of using heavy applications of nitrogen without the danger of lodging. The characteristics of the two-rowed barleys, as described here, have given this crop the

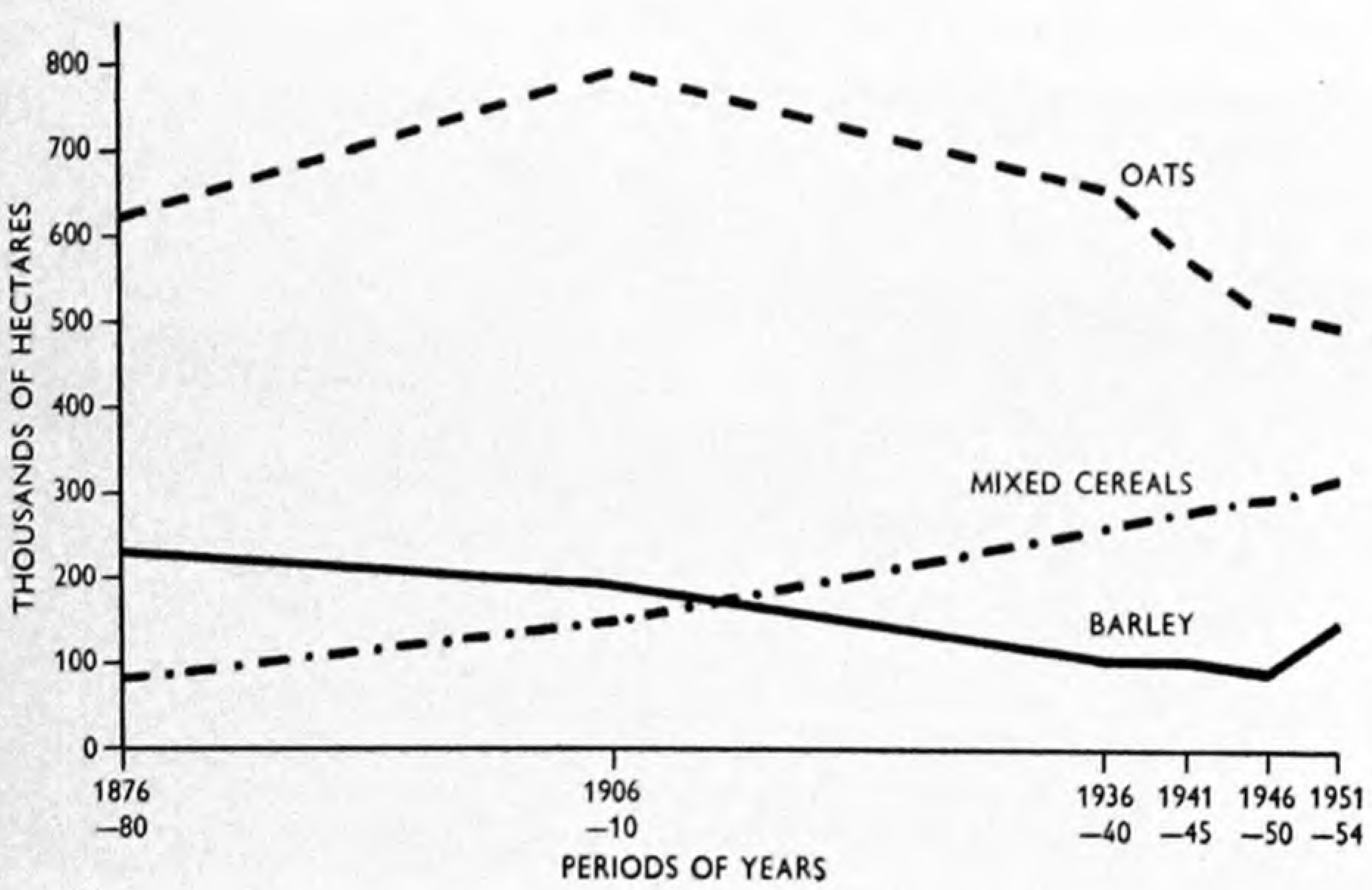

FIG. 3. Acreages of barley, oats, and mixed cereals during the period from 1876 to 1954.

standing of a crop for good soils on intensively managed farms. In part this explains the increasing acreage of barley since 1951. It is a good development, but still it is not without disadvantages. It has been shown above that wheat has increased in acreage. Winter and spring wheats are very often grown on the same farm. With an increasing acreage of barley on these farms also there is a danger of increasing attacks of foot rot diseases (*Ophiobolus* and *Cercosporella*). Such attacks have been observed more frequently on both wheat and barley during the last few years and must be watched for in the future.

The breeding work with two-rowed barley at the Swedish Seed Association in Svalöf resulted in 1899 in the release of the variety SVANHALS. It is still available. Among other early released varieties mention should be made of GULL (released in 1913). During a period of 15 to 20 years a number of Danish varieties were widely grown in Sweden. Such varieties were BINDER, OPAL, KENIA, and MAJA. Later came FREJA

(1942) and YMER (1945) from Svalöf and BALDER (1942) from Weibullsholm. Around 1950 came those varieties which have been so important for the present high yields of barley. They were HERTA (in 1949) and RIKA (in 1951) from Weibullsholm, and HEIMDAL and BONUS (both in 1950) from Svalöf. Of these HERTA and RIKA have an extremely stiff straw and good ability to withstand poor weather conditions in the field when ripe for combining as shown in Fig. 4. However, they do not have outstanding malting qualities. HEIMDAL does not have as stiff a straw as HERTA or RIKA but it has better malting qualities. So far no variety has been released that has a really good malting quality combined with a stiffness of straw like that found in HERTA and RIKA; this is undoubtedly a weakness in the material of two-rowed barleys in Sweden.

FIG. 4. Combining two-rowed barley, which was left in the field long after it was ripe for combining because weather had been unfavorable for harvesting. Ultuna near Uppsala, Sept. 22, 1950.

HERTA, RIKA, HEIMDAL, and BONUS are, however, grown for the production of malt, but they are grown for that purpose in three main areas in the country. These are the western parts of the southernmost province (Skåne), on the island of Gotland, and the western parts of Östergötland (near Lake Vättern). From these areas products good for malting are usually obtained. The yields of the two-rowed barleys are normally about 4000 kg. per hectare. As the six-rowed barleys are grown mainly in those areas of the country where earliness is an important feature they do not yield as much as the two-rowed types. But there are really no requirements that they should do so. In fact the six-rowed barleys are used mainly for fodder production under conditions where oats is the main competitor. Consequently six-rowed barleys should be compared with early oat varieties rather than with two-rowed barleys. This has become even more important in recent years since severe parasite

attacks on oats have appeared in parts of northern Sweden. These attacks must be ascribed to unbalanced crop rotations. In those areas six-rowed barleys are now replacing oats, as the barleys are found to be resistant to the parasites. Rotations including barley, temporary leys of clovers and grasses, and potatoes or fodder roots seem to help the farmers in these areas.

For the purpose of replacing oats in parts of northern Sweden the six-rowed barleys should be early, i.e., they should be able to develop from seeding to harvest in 75 to 90 days. The need for earliness in six-rowed barley has, however, long been known. In northern Sweden early types like EDDA I and EDDA II do not need more than about 85 days for development from seeding to harvest. ÅSA is even earlier. Types like these will in most summers give ripe yields of barley far up into the north, i.e., to 67° to 68° N. If the crop does not ripen because of unfavorable conditions, it can at least be used for green fodder production. Compared to varieties grown in northern Sweden in earlier times these varieties also give good yields. Because of the difficulties of producing seed under extreme northern conditions it will be necessary to produce certain amounts of the seed of these six-rowed barleys in middle Sweden, where one of the weaknesses of the six-rowed barleys is likely to show up. When they are left in the field for combining, the rather weak straw may result in lodging or broken stems and heads. This will happen particularly if the crops must be left in the field fully ripe for a few days. A good step forward in the six-rowed barley should therefore be varieties with better straw and better resistance to straw and head breaking than is normally found in present varieties.

Under such circumstances the aim for future breeding of six-rowed barleys should be to arrive at a satisfactory earliness, a good quality of straw, good yielding ability, and increased resistance to diseases, such as mildew and leaf rust. With further progress in these respects six-rowed barleys should have good possibilities of competing successfully with oats, which have for a number of years been the dominant cereal in northern Sweden. In many respects this should mean progress in crop production in that part of the country as crop rotations with temporary leys of clovers and grasses, oats, potatoes, and fodder roots are rather unbalanced as far as the cereal is concerned. Oats should alternate with six-rowed barleys.

4. Oats

The oat crop is important in Sweden. In former periods the acreage was very high and the crop was grown on every farm. During a period of years it was also exported to England in large amounts. The high

acreage of oats has been closely connected with the production of feed for horses. Since horses in Sweden are decreasing very rapidly—there were 362,000 in 1953 as against 716,000 in 1919—the need for oats for feed has also decreased. This, together with the campaign during World War II for a replacement of a certain acreage of oats with protein-producing crops, has led to the lower acreage of oats since 1946 which is noted in the figures in Table I. The average total yield of oats in Sweden during recent years has been 700,000 to 800,000 tons. Of this amount only 50,000 to 70,000 tons are used for food, the rest for feed for horses, cattle, and chickens.

Oats are grown all over the country, but on the plains in south and middle Sweden the oat crop has often been replaced by higher producing and better paying crops. Oats are therefore now found mainly in the uplands or on the organic soils in south and middle Sweden and more generally in northern Sweden. The types of oats in Sweden all belong to *Avena sativa.* They are white and yellow oats, which are usually considered as one group, and black oats, which is another group. Black oats are found in a limited area of middle Sweden, i.e., at the western end of Lake Mälaren and in the surroundings of Lake Hjälmaren. They are, however, most extensively used in northern Sweden. In the Mälaren-Hjälmaren area the black oats are very well adapted and able to develop well during the dry early summer. In northern Sweden the early black oats are well adapted to the short growing season. In other parts of the country white and yellow oats predominate or are the only ones planted.

Although oats was adopted as a cultivated plant later than barley and originally appeared as a weed in barley, oats have predominated over barley during the last 100 years. In earlier periods oats were grown in all areas of the country, but now, as mentioned above, they are more and more confined to the upland areas, the somewhat poorer soils, many organic soils, and soils where the drainage is not well taken care of. In other words, oats have proved to be a safer crop in areas and on soils where the growing conditions are not ideal. This is undoubtedly an important reason why oats have been and still are so widely grown in Sweden, where there are many places with natural conditions that do not allow the growth of crops with high requirements. This is also the reason why the oat acreage remained high until World War II, at which time certain acreages in the country had to be set aside for new crops necessary for food production. This decrease has then continued during the present period of mechanization. In addition to the above reasons for keeping oats there are others, some of which are worth remembering today, when the crop rotations in Sweden show a tendency to become

unbalanced and cereals occupy a large percentage of the fields in the rotations. Oats are not susceptible to those foot rot diseases which are serious on wheat and barley, and are therefore excellently suited for alternation with wheat and barley. This is also done at present and the

FIG. 5. Oats being dried in the field on "krakstör." Ultuna near Uppsala, 1949.

oats are then used for feeding the cattle. Many times they are mixed with barley. On farms where foot rot diseases are no problem, such mixtures are very useful and safer in yield over a number of years than oats alone. The farmers are well aware of this, as witness the figures for mixed cereals. Mixtures were grown on 81,194 hectares per year during

the period 1876 to 1880, on 153,045 hectares in 1906 to 1910, and on 259,793 hectares in 1936 to 1940. In the five-year period 1949 to 1953 there were 318,944 hectares per year. These figures should be remembered when the relation between cereals for feed is discussed. There is now an interest in mixtures of oats and peas, thereby adding to the oat crop a leguminous crop with a good protein content. Mixtures of oats and peas usually consist of 75 to 85 per cent oats and 15 to 25 per cent peas, figured on the normal seeding rates of each of the two crops.

The long-maintained interest in oats has carried with it an intensive breeding program which has mainly aimed at stiff straw, earliness, resistance to attacks by insects and diseases, good yield, and good kernel quality. Of the breeding results with white and yellow oats the variety SEGER should be remembered as one of the most outstanding breeding products from the Swedish Seed Association in Svalöf. GULDREGN I and GULDREGN II have also been outstanding. In recent years types such as SOL II (1943), BLENDA (1950), TRIO (1943), and REX (1953) have brought oat production per hectare still higher. To these white and yellow oat varieties should be added black oat varieties for middle Sweden, such as STORMOGUL II (1932) and ENGELBREKT II (1931), and very early types for northern Sweden such as ORION III (1946) and SAME (1943). The last-mentioned four varieties originated at Svalöf.

5. *General Remarks on the Cereals*

The discussion of the four cereals undoubtedly shows that these are of great importance in Swedish crop production. Even though there are changes in the acreages of different cereals, the total acreage is approximately the same now as 75 years ago. Of the cereals and the mixed cereals there were in 1876 to 1880 1,368,000 hectares. In 1936 to 1940 the acreage was 1,515,000 hectares and during the five-year period 1949 to 1953, 1,615,000 hectares. In per cent of the total acreage of cultivated lands these figures are 48.3, 40.6, and 43.3. These figures show that although there are significant changes in each one of the cereals, these changes have not influenced the relationship between the cereals and other crops. The percentage of cereals in today's modern and mechanized agriculture is not more than 5 per cent lower than it was during the period 1876 to 1880. Immediately before World War II the difference was greater. This arises from the fact that at that time well-balanced crop rotations existed to a larger extent than today, and farming without cattle was of little importance. Fodder crops were at that time more common than today. The figures for the cereals show that in Sweden, where cereals and grasses are the original field crops, the cereal is still holding its ground. It is most interesting to compare these

observations with the ones that can be made in regard to the grasslands or rather to the lands used for clovers and grasses.

6. Temporary Leys and Natural Grasslands

In discussing crop rotations it was mentioned that grasslands, and later temporary leys, alternated with cereals. There were cereals for three or four years and temporary leys for four to ten years. The temporary leys in such rotations cannot have been good leys for more than two or three years. After that period of time they were not very much better than natural grasslands which were also used for hay or grazing. In Fig. 6 it will be seen that the total area in temporary leys

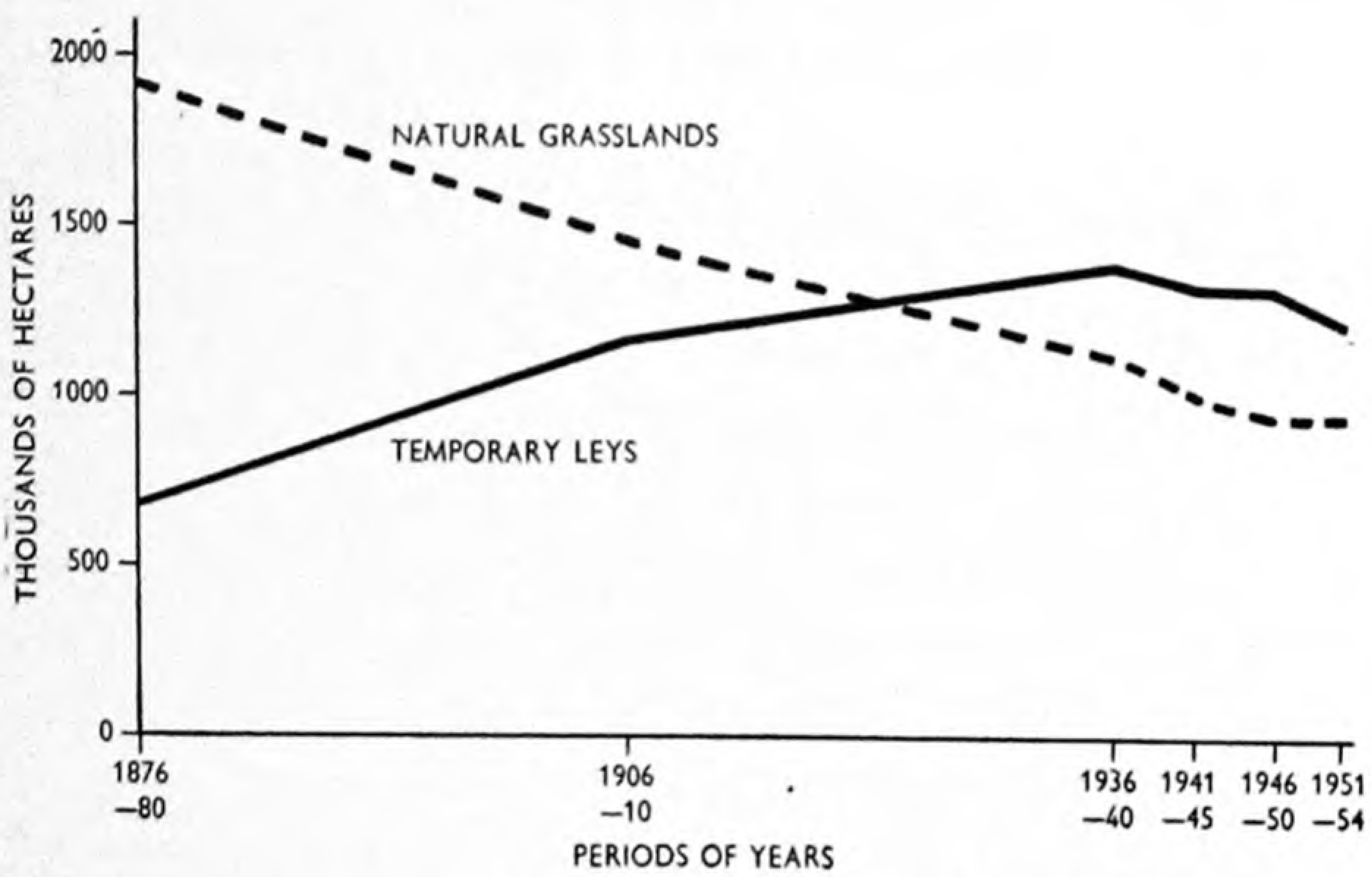

FIG. 6. Acreages of temporary leys and natural grasslands during the period from 1876 to 1954.

and natural grasslands was rather high during the period 1876 to 1880 and also that the natural grasslands dominated. In 1906 to 1910 a similar situation existed, although the natural grasslands then occupied a smaller acreage than 30 years earlier. The trend after 1910 definitely favored the temporary leys, and in recent years natural grasslands have held a constant acreage that is lower than that of temporary leys. At the same time the acreage of temporary leys increased up to and including 1947, but decreased again after that year. The latter development is closely connected with those changes in numbers of cattle which were mentioned above, and can consequently be referred to the increasing percentage of farms without cattle. It is also a result of higher producing leys of clover and grasses, which have resulted from better methods of establishing and managing these leys as well as the cultivated pastures. The very great achievements in this field in Sweden are a result of

better care of the leys and the pastures, as well as the breeding of varieties and strains of forage crops better adapted to our conditions, and with better production capacities than the ones used earlier. The changes in management of established leys and pastures have been rapid during the last two or three decades. Nevertheless there is still a great need for improvement in this field.

Great steps have been taken from the period when temporary leys were started with the seeds that were found under the hay in the barns up to the present, when emphasis is put on a high quality of seed for the leys. There have been tremendous improvements in this field during the last 20 to 30 years, arrived at through cooperation between the Association of Seed Producers and the seed testing stations. These questions will be touched upon in a later section.

The types of temporary leys vary between the different parts of the country. On the plains in southern Sweden the leys occupy a rather small part of the land, normally about 25 per cent. Leys intended for hay are used only for one or two years and therefore mainly consist of red clover or alfalfa, alone, or together with a small amount of grasses such as perennial ryegrass, meadow fescue, orchard grass, and timothy. On the plains in middle Sweden the temporary leys occupy between 30 and 40 per cent of the cultivated land. The ones for hay are used somewhat longer than the ones on the plains in the southern parts, i.e., for two or three years. Still the most common plants in the mixtures are red clover and grasses, although red clover has in recent years sometimes been mixed with alfalfa. This is particularly the case on well-drained soils with a good lime content, provided the leys are intended to be used for three or four years. Thus red clover alone or in mixture with alfalfa is used together with grasses such as timothy and meadow fescue. Quite often alsike clover in small amounts is brought into the mixtures as an additional legume. In the uplands of south and middle Sweden and on peat soils 40 to 55 per cent of the cultivated land is in temporary leys (Fig. 7). On the mineral soils these are mainly of the type mentioned for the plains in middle Sweden. But the leys for the peat soils are different in composition. They are seeded with higher amounts of grasses than the leys on the mineral soils. Thus timothy and meadow fescue are used in the seed mixtures for these soils, with approximately the same amount of seed per hectare as that of red clover. In northern Sweden temporary leys occupy between 60 and 75 per cent of the cultivated land. The main components in the leys intended for hay are red clover, alsike clover, timothy, and meadow fescue. These leys are planned to last three years and therefore the grasses occupy a larger part of the seed mixtures than the clovers. On the basis of experience

and experiments ÅKERBERG *et al.* (1950) recommended for the plains in south Sweden legumes alone or in mixtures. In the latter ones the grass seeds are 5 to 7 kg. per hectare, while the red clover seeds, usually of an early type, are 15 to 17 kg. On the plains in middle Sweden mixtures of 8 to 12 kg. grass seeds and 12 to 14 kg. red clover seeds can be used. Should alfalfa be included the figures should instead be 8 to 11 kg. of clover seeds, 8 to 10 kg. of alfalfa seeds, and 8 to 10 kg. of grass seeds per hectare. In the uplands the figures for the seeds are 10 to 12 kg. of the grasses and 11 to 14 of the clovers. On peat soils the figures are 18 to 20 kg. of the grasses and 10 to 12 kg. of the clovers. Medium early types

FIG. 7. Temporary leys, used for pastures in middle Sweden. Bergsbrunna near Uppsala, 1953.

of clovers should be used in these areas. In northern Sweden medium early to medium late types of red clover are recommended. The mixtures usually include 18 to 20 kg. grass seeds per hectare and 10 to 13 kg. clover seeds. In pastures established on cultivated lands there is very little red clover or alfalfa. If they are used it is for improving the stand during the first year. The amounts of seed per hectare may then be 3 to 5 kg. Plants for a long-lasting pasture are white clover (15 per cent) and grasses (85 per cent). The grasses are Kentucky bluegrass, rough bluegrass, perennial ryegrass, meadow fescue, red fescue, and bent grass in different amounts depending on the soils. On dry soils in south and middle Sweden meadow fescue, red fescue, and Kentucky bluegrass dominate, and on wetter soils the bluegrasses, perennial ryegrass, and meadow fescue. In northern Sweden the proportions are approximately

the same, or more bent grass may be added to the mixture. The ratio between temporary leys for hay and for pastures varies in different parts of the country. In south Sweden the pastures are about one-third of all established leys, in middle Sweden one-fourth to one-sixth, and in northern Sweden only one-twentieth to one-thirtieth. This must be seen against the background of the proportions of natural grasslands in different parts of the country. In northern Sweden these are much more common than in southern Sweden. Many of these natural grasslands are now fertilized, renovated, and managed as cultivated pastures; others are still used without being fertilized or improved in any way. In a publication by Giöbel and Åkerberg (1953) there are more details on Swedish grasslands.

The temporary leys for hay naturally become clearly characterized by the components used for seeding them. In south Sweden where the leys are used only one or two years, there are no remarkable changes in the stand, even though in the two-year-old leys it may be thinned by attacks of clover stem rot (*Sclerotinia trifoliorum*) and clover nematodes (*Ditylenchus dipsaci*). The situation is worse in middle Sweden, where the leys are used two or three years. In these leys the stand is often seriously thinned out because of attacks of one or both of the parasites mentioned (Bingefors, 1948, 1950). This means that the third-year ley becomes weedy. Because of this there is now a definite tendency towards two-year leys. In northern Sweden the leys are still used three or four years. They may even become older and these old leys often consist of a mixture of a few clover plants, grasses, and weeds.

It is a big task for the future to improve the leys with regard to longevity. Only 30 or 40 years ago most of the leys were undersown in fall-sown cereals. In areas with low rainfall during the spring and the early summer months this gave, in most cases, a poor stand, as can be exemplified with results from Ultuna near Uppsala (Åberg, 1946). The yields from the leys the first year after they were seeded were 17.5 per cent higher when the leys were seeded in a spring-sown crop than they were when they were seeded in a fall-sown one. In most of the country during the last 15 years it has become established practice to seed the leys for hay in spring-sown crops such as barley, spring wheat, and oats. Likewise it has become a custom during the two last decades to seed in rows instead of broadcasting the clover and grass seeds. Results published by Åberg (1947, 1949) and by Lundblad (1953) have shown that the increase in yield due to seeding in rows instead of broadcasting can be as high as 10 per cent. The problem at present is how to retain the good stand of the first-year ley during the period of two or three years that the leys are kept, or should be kept, in most parts of the country.

Parasite attacks, thinning by winter damage, and poor methods of fertilizing and management are responsible for the rapid decline in yields of some of the established leys. To achieve improvement there is a need for clover types that are resistant to the parasites, for the use of balanced crop rotations in which there are six to eight years between the leys, and for the education of farmers in regard to the use of fertilizers on the leys and their general care. Varieties resistant to the parasites are needed in the country as a whole; improvements in regard to the care of leys are especially necessary in northern Sweden.

It has been pointed out repeatedly that the breeding of new varieties and strains of clovers and grasses is a necessity for good yielding leys. The breeding of forage crops in Sweden does not date back as far as the

FIG. 8. Hay-making time in the valley of Ångermanälven in northern Sweden. Near Sollefteå, 1952.

cereal breeding, but nevertheless it has resulted in satisfactory developments. The breeding of red clovers has to a great extent been based on local strains. A local strain that has been of importance for middle Sweden is ULTUNA. Strains that are fairly resistant to clover stem rot and nematodes are MERKUR from Svalöf and RESISTENTA from Weibullsholm. They are both medium early. Right now special interest is offered by the tetraploid types of red clover, which are being tested in different parts of the country. Tetraploid types of alsike are also being tried, and a tetraploid strain of alsike clover, TETRA, has been released from Weibullsholm. It was produced by Professor G. Turesson at the Institute of Plant Systematics and Genetics of the Agricultural College in Uppsala. Good results have also been obtained with a number of other forage crops. In timothy there are, for example, GLORIA and KÄMPE II from Weibullsholm, VANADIS from Hammenhög, and OMNIA from Svalöf. They are first of all intended for south and middle Sweden but can also be used further north. OMNIA, for example, can be used in

good locations in northern Sweden, but BOTTNIA is the main variety for northern Sweden and is used extensively in that part of the country. In the same way there are varieties of other grasses both for hay and pastures in different parts of the country. All these varieties or strains of forage crops show that the breeders have been successful in producing material which is greatly superior to the old local types. During the last 40 years about 70 new breeding products have been released, about 30 of these in the last two decades. It is difficult, if not impossible, to evaluate the influence of these new products in the increase in yield from the established leys, but there is no doubt that, together with better growing methods for the leys, they have contributed substantially to production from leys in Sweden.

So far reference has been made primarily to improvements in yield and stand and nothing has been said about the quality of the products. Improvement in quality has been observed for the leys and studies of better methods for growing and harvesting are under way. For a number of years the principle of harvesting the leys for hay at the stage when the red clover starts flowering has been applied in Sweden. In this way a better quality is obtained than would be the case if the cutting was done later. The influence of different stages of development and environmental factors on quality has been taken up in detailed studies especially by Julén at the Swedish Seed Association in Svalöf.

Consequently the future work on temporary leys in Sweden will deal with the methods of improving both quality and quantity of hay and other products from these leys, and can be expected to emphasize the quality.

A comparison between the development of the grasslands, both improved and natural, and the development of the cereals shows that to date greater efforts have been made to improve the cereals than to improve the grasslands. Even so, the development of grasslands has been impressive. The grasslands, like the cereals, have remained a main crop in Swedish agriculture. During the period 1876 to 1880 established leys were found in 28.6 per cent of the total area of cultivated lands. In 1936 to 1940 they were found on 41.8 per cent, in 1941 to 1945 on 43.3 per cent, and in 1949 to 1953 on 43.1 per cent. There was a continuous increase in the acreage of established leys up to 1947, when it started to decline. This trend is suggested in the above figures. Simultaneously with this development the natural grasslands have decreased. In relation to the cultivated area they were 67.3 per cent in 1876 to 1880, 30.2 per cent in 1936 to 1940, 26.8 per cent in 1941 to 1945, and 25.2 per cent in 1949 to 1953.

The area of cultivated land has increased by 900,000 hectares since

the period 1876 to 1880; during the same period the area of natural grasslands has decreased by 1,000,000 hectares. Simultaneously the acreage of established leys increased by 750,000 hectares. In view of the fact that the yields per hectare have increased, this means that the grasslands are today as important in Swedish agriculture as they have always been. The higher yields per hectare have made possible at least the same total yield of hay today as during earlier periods, in spite of the fact that the total acreage of grasslands is somewhat lower. This is also illustrated in the figures for total yields. These show, for example, that the yields of hay from established leys and natural grasslands were 4,209,778 tons in 1916 to 1920 (the first period when these figures are available), 5,142,509 tons in 1936 to 1940, and 5,031,884 tons in 1949 to 1953. Thus cereals and the combination grasses-clovers are still the two main crops in Sweden and constitute the background to the crop production of modern times as well as in older days.

7. *Potatoes*

In Table I it is easily seen that potatoes have been grown on approximately the same acreage during the last two decades. They are grown for food and feed, and only in limited areas for the production of alcohol and starch. The developments during the last two decades have mainly been concerned with better varieties in regard to yield, quality, and disease resistance, but they have also dealt with the possibilities of limiting the number of varieties used in the country. The objective of this has been to arrive at a few good varieties that can be grown, instead of a great number of varieties of which some are good and others are poor. Hagberth (1951) discussed this problem on the basis of an investigation carried out in the years between 1937 and 1943. He studied 11,000 samples from different parts of the country and found 200 varieties represented. Of all the samples 48 per cent were pure and 52 per cent mixed. There were 59 per cent correctly named. Great efforts have been made in recent years to arrive at a concise list of potatoes that can be recommended to the farmers. Such a list is now prepared every year by "Sveriges Potatisodlares Riksförbund" (The National Association of Swedish Potato Growers). It contains about 25 varieties, arranged according to earliness, quality, and special qualifications for food, for starch and alcohol, or for feeding purposes. This list has meant a great step forward in the campaign for better potatoes.

For the production of seed potatoes of high quality there has been an intense campaign and rigorous testing, not only for pure varieties but also for virus-free seed. For a number of years the work in this field has been carried out by Hellbo and his co-workers at the Government

Seed Testing Station in Stockholm. This work includes studies of the seed potatoes in the laboratory and in the field, as well as field inspections. Great improvements have already been made but much remains to be done. The problems connected with the growing of seed potatoes of high quality are also studied closely by Emilsson and cooperators at "Institutet för växtforskning och kyllagring" (The Institute for Plant Research and Cold Storage) at Nynäshamn.

The problems discussed above, together with methods of combating the *Phytophthora* disease, seem to be the main ones in potato production. This means that breeders in addition to yield will have to pay

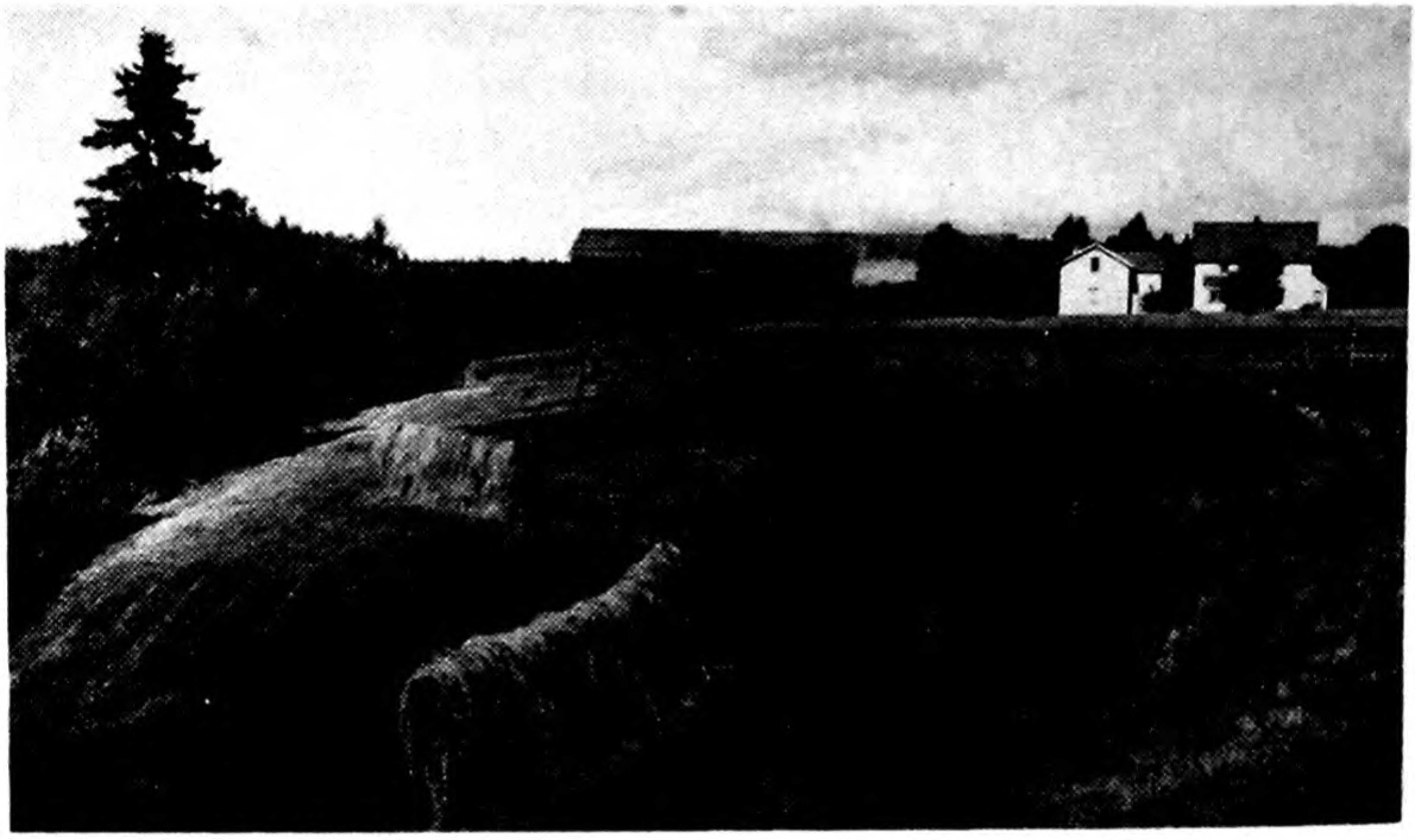

FIG. 9. A small farm in northern Sweden. The ley is bordering the forests, the corner of the potato field is seen at right, and the cereal field in the background. Resele near Sollefteå, 1952.

attention to disease resistance and cooking quality in order to get their products in the list of recommended varieties. Among the best potato varieties used in Sweden are several foreign ones, for example, the Dutch variety BINTJE and the English varieties KING EDWARD VII and MAGNUM BONUM and also indigenous ones such as MANDEL (for northern Sweden) and the new Swedish ones as EVA, BIRGITTA, and ELSA from Svalöf.

8. Fodder Roots and Sugar Beets

Turnips and *swedes* have been grown in Sweden for hundreds of years. In the same way as cereals and grasses, they are old crops in the country. *Fodder beets,* like the *sugar beets* originating from *Beta maritima,* were not grown until the latter part of the 19th century. At

the same time as there developed an interest in sugar beets at the end of the 19th century, there arose an interest in fodder beets (Table I). An increase in the acreages of fodder roots is also evident up to 1940, but after that time there was a decrease (Fig. 10). The disposal of the cattle on a number of farms has partly caused this decrease. Another reason is the introduction of silage crops which can be harvested by machines more easily than the root crops. The rising costs of hand labor have speeded up this development, and there is a steadily declining curve for fodder beets in Sweden, in spite of the fact that the soils are good for such a crop and there is an obvious need for it. Not until the growing of fodder beets can be mechanized to a greater extent

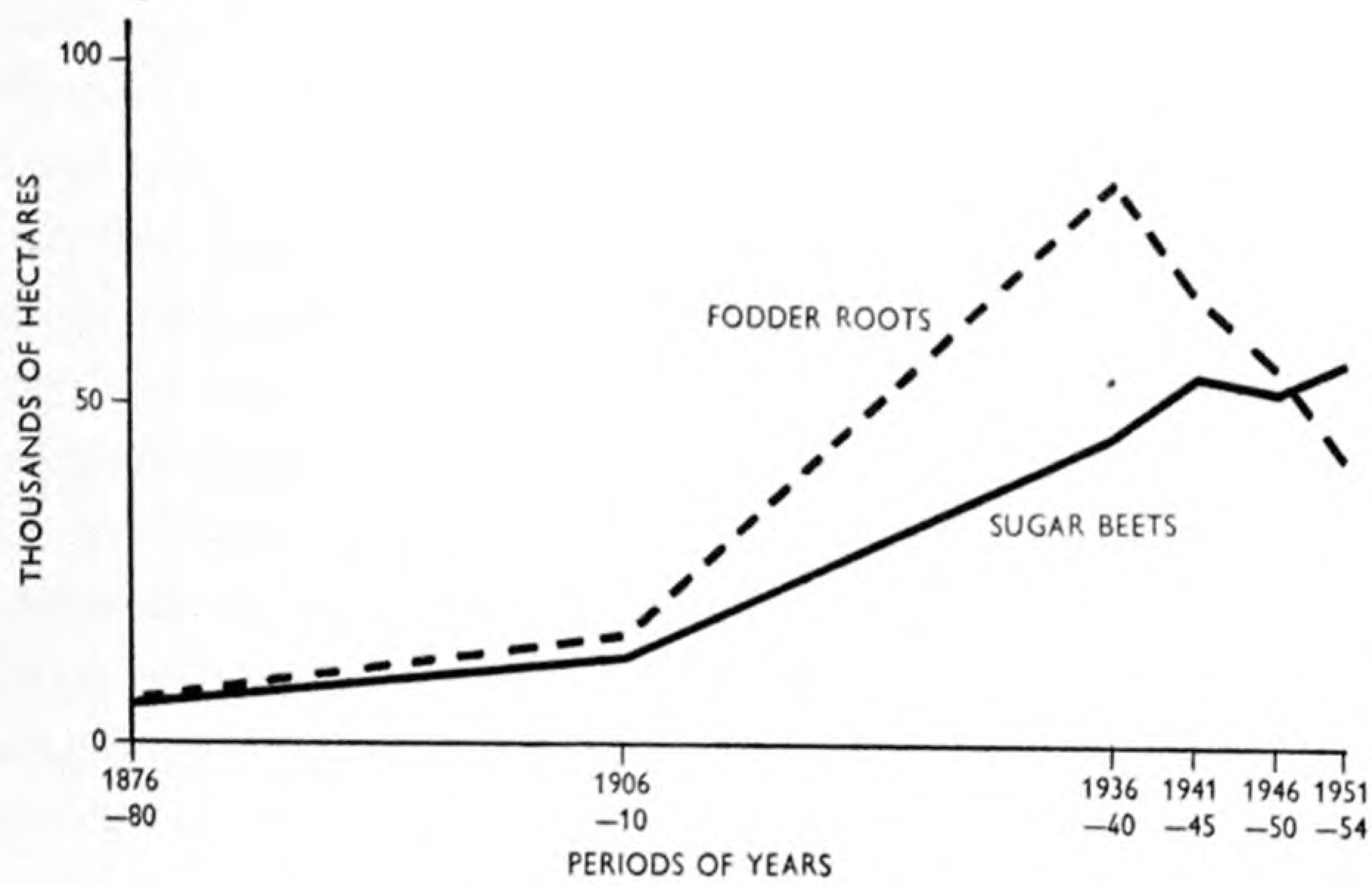

FIG. 10. Acreages of sugar beets and fodder roots during the period from 1876 to 1954.

than is now the case will there be a possibility of a return to this crop. As things are now, fodder beets are grown only on small farms or on farms where hand labor is easily available.

The breeding of fodder beets in Sweden has in recent years brought several new varieties that are very good yielders and represent the new development in this field, i.e., varieties with a higher dry matter content than was the case 20 or 30 years ago. The new varieties of fodder beets have dry matter contents between 15 and 20 per cent or approximately 5 to 10 per cent more than the old varieties.

Sugar beets would perhaps not have been more popular than the fodder beets had it not been for the price set on sugar beets together with the high qualifications of the crop for inclusion in the intensive crop rotations in southernmost Sweden. For it must be remembered that sugar beets are grown mainly in Skåne, the southernmost province in the country. In this province 82 to 83 per cent of the total acreage of

sugar beets are found. The production is on contract between the farmers and the Swedish Sugar Company, and the acreage has therefore been rather constant in recent years. The seed is obtained from the sugar company, which also has a breeding station of its own at Hilleshög near Landskrona. The varieties used are therefore well adapted to the climatic conditions under which the sugar beets are grown.

In order to encourage the farmers to continued production of sugar beets inside the country the Swedish Sugar Company has made great efforts in investigating the possibilities of mechanizing sugar beet growing. The investigations have been especially intensive during the period since World War II. Sheared seeds have in recent years been used on a number of fields; in 1953 on 26.8 per cent and in 1954 on 34.2 per cent of the total area of sugar beets. Mechanized harvesting of the sugar beets has been very intensively studied but is in many cases difficult to carry out because of the heavy soils and the frequent rains in south Sweden during the period of harvest. Although marked progress is made, it is therefore still a question for the future as to when mechanized harvesting will be the prevailing method of harvesting. Among the diseases on sugar beets virus yellows is at present the one causing the greatest trouble. Heart rot and other diseases caused by deficiency of micro-elements are taken care of by adding these elements in the fertilizers. Nematode attacks have been rather serious in recent years and seem to bring another problem to Swedish sugar beet production.

9. Legumes

The legumes in Sweden at present are peas, vetches, kidney beans, field beans, and soybeans. Among these interest is centered on peas. Vetches are grown for green fodder and for seed to the extent that green fodder production is secured. Kidney beans are grown on special areas in southeastern Sweden and do not occupy any large acreage, field beans are found in a small area in the archipelago north of Gothenburg, and soybeans are grown on a small acreage in southeastern Sweden, mainly on the island of Öland.

Peas are grown for cooking (yellow peas), for canning, and for fodder. The acreage of peas went up slightly during World War II, when there was a need for as high a production of protein inside the country as possible. After the war it again decreased and the acreage is now lower than it was before the war. The reason for the lack of interest in continued growing of a large acreage of peas is the unreliability of the crop in regard to production: under Swedish climatic conditions the yields may be good one year and extremely low the next.

In spite of this situation there is an interest in improving the crop

and finding better methods for growing it. The breeding of yellow peas has dealt with increased yield and resistance to disease attacks, mainly by *Fusarium* species. The quality, too, has been studied in this respect, and for a number of years the possibilities of breeding for quality were intensely studied at the Ultuna Branch Station of the Swedish Seed Association. After these studies were combined with studies by Mattson in regard to the influence of environmental factors on the cooking quality, Mattson (1946) showed that the cooking quality of the peas depends, to a high extent, on the content in the peas of phytin (inositol phosphoric acid). This has been found to be higher in soft cooking than in hard cooking peas. Investigations by Mattson *et al.* (1950) showed that phosphate increases the phytin content of peas, which then become more cookable. Peas grown on soils rich in soluble phosphate are rich in phytin. If they are also fully ripe, they will be easy to cook.

Canning peas are grown in certain areas around the canning industries. The production is based almost entirely on imported seed.

For fodder peas the breeding also aims at higher yields, disease resistance, and a better quality, which in this case is a problem of increased protein content in the seed and good feeding value of the peas in the green fodder stage.

The possibilities of harvesting peas with the help of a combine have, for a number of years, been studied by Andersson and Åkerberg (1954), who reported that it is possible to thresh peas from the windrow with a combine harvester.

10. Oil Crops

It is clear from Table I that the present oil crops growing in Sweden are of recent date. In 1941 to 1945 there were only 28,000 hectares, and in 1939 and 1940 there were only two or three hundred hectares. This was when the cultivation of oil crops was again taken up after it had completely disappeared after World War I, when some winter rape and white mustard had been grown. During the period 1941 to 1945 the acreage gradually increased and was 37,719 in 1945, whereas it had been only 8151 hectares in 1941. But the really important development came after the end of World War II (Fig. 11). The highest acreage was obtained in 1951, when 190,000 hectares of oil crops were grown. The decrease after that year has meant that at present the acreage is about 100,000 hectares, which seems to be an acreage on which enough can be produced to meet the needs in the country and sometimes to allow for export. The rapid increase after the war can be explained by the price policy which made oil crops strong competitors to the cereals. The decrease in recent years is explained by the severe attacks of insects and

diseases which followed as a result of the intensive growth of oil crops, especially in south Sweden. Although the oil crops were in the early 1940's grown almost entirely in the southermost parts of Sweden, where they were first introduced, they are now grown not only in south Sweden but also in middle Sweden. In fact very good results are now obtained from the growing of oil crops in middle Sweden.

A very noticeable development is the change-over from spring-sown oil crops to fall-sown ones. During World War II there was a very great interest in spring-sown rape, white mustard, oil flax, and poppies. These were found on the same farms as the fall-sown types. When the insect attacks became serious, the growing of spring-sown and fall-sown rape on the same farm gave rise to great problems, as the insects alternated

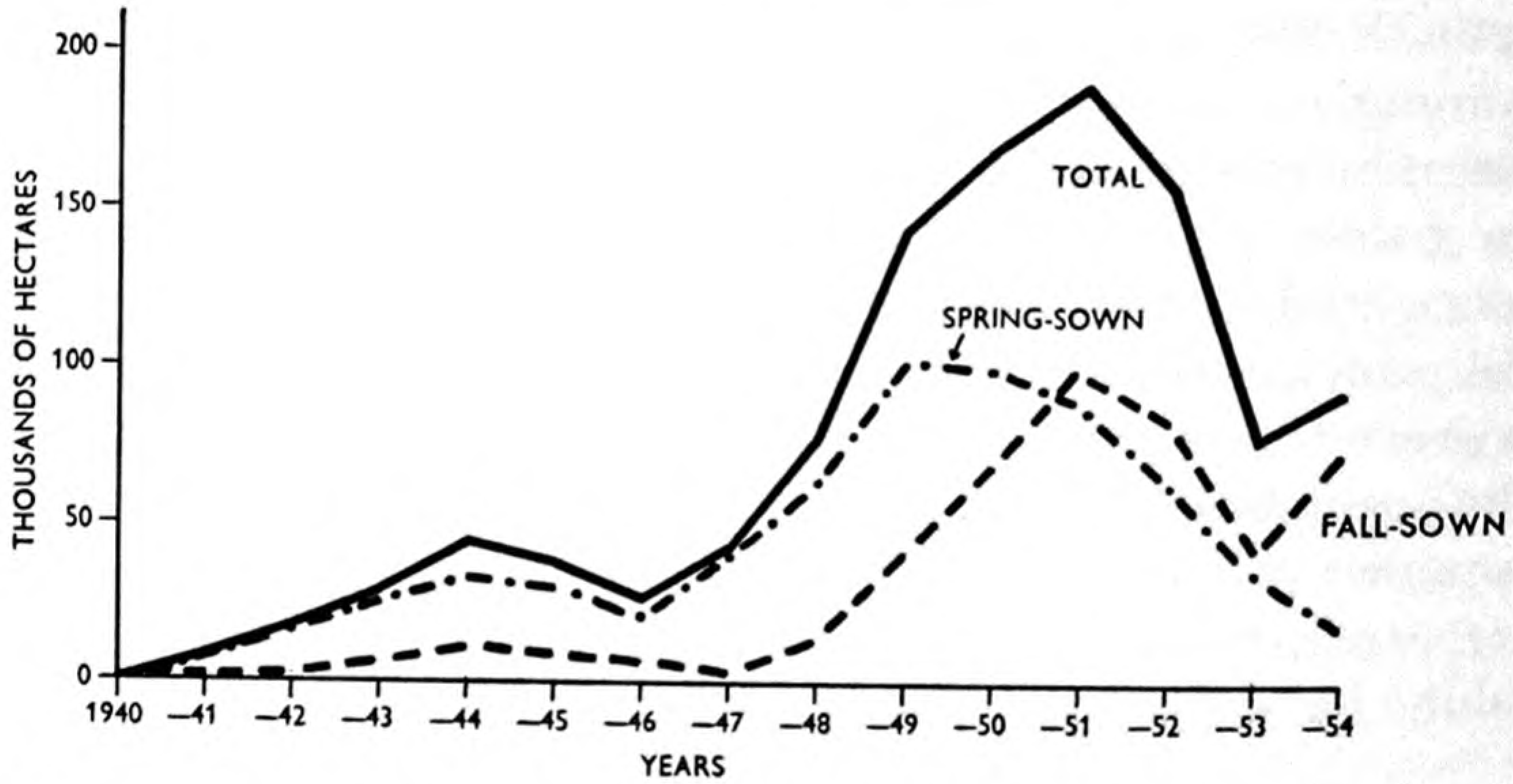

FIG. 11. Acreages of oil crops during the period from 1940 to 1954.

between the two types of crops. Even though it seemed unbelievable at first, it soon became evident that the fall-sown types of rape and turnip rape took the lead and now seem to develop into the main oil crop in Sweden from the areas just north of Stockholm to the extreme south. The turnip rape has proved to overwinter better than rape and is therefore used in the localities where the climate is hard. Intensive studies of the overwintering problems in oil crops are now carried on at the plant breeding stations and at the Institute of Plant Husbandry of the Agricultural College in Uppsala. Fall-sown oil crops in south and middle Sweden are usually grown once per crop rotation, i.e., once every sixth or eighth year. In this way they become good contributors to crop production and to the improvement of crop rotations, where they are suitable for alternating with cereals and leys.

The work of the plant breeders has also contributed to this development in oil crops. They have produced better varieties with good yields,

better over-wintering ability, and better quality. Of fall-sown rape there are, for example, TENUS and MATADOR from Svalöf and of fall-sown turnip rape STORRYBS from Weibullsholm and RAPIDO from Svalöf. Of spring-sown rape there is REGINA and of spring-sown turnip rape the variety GUTE. Both are from Svalöf. Of white mustard the variety PRIMEX should particularly be mentioned. Oil flax is not grown extensively, even though it should fit well into the crop rotations in Sweden and there are good varieties of it, e.g., VALUTA from Svalöf.

11. Miscellaneous Crops

During recent years various crops have been tried in Sweden, and some of them have gained importance. It is well known that clover, alfalfa, and grasses are the most commonly used crops for silage in Sweden. Nevertheless *sweet lupine* has been introduced on sandy soils and peat soils, *hybrid maize* is being tried in southern Sweden and in parts of middle Sweden, and *marrow stem kale* is of interest in different parts of the country. A detailed study of new silage crops is under way at the National Agronomy Experiment Station in Uppsala.

Fiber crops are grown, to a limited extent. *Fiber flax* is grown more frequently in southwestern Sweden than in any other place, and *hemp* is grown on the island of Gotland, where the soils are rich in lime and humus and therefore well suited for growing this crop.

For a number of years *vegetables* have been grown as regular farm crops on the island of Öland, in southeastern Sweden, and in parts of southwestern Sweden (mainly in Skåne). The canning industry has developed rapidly since World War II, and the growing of vegetables, berries, and fruits within certain areas is increasing. Especially within the areas earlier used for these crops, there is a marked upswing.

Finally it should be mentioned that the *rubber dandelion* (*Taraxacum koksaghyz*) has been studied since World War II. Although its value has so far been negligible for practical purposes, it is mainly grown for studies envisaging a possible adaptation to Swedish conditions.

12. Seed Production and Seed Testing

It is naturally of great importance that the seed of crops typical for the country be able to be produced inside the country and that it be of high quality and of the right varieties for the different areas. As Nilsson-Leissner (1954) pointed out, seeds of cereals and legumes are produced all over the country, with the exception of lupine seed, which is produced in southern Sweden. Seed of red clover is harvested in the whole country up to the Arctic Circle and seed of alsike clover in south and middle Sweden. Timothy is grown for seed all over the country

and other grasses in southern Sweden. Seed of alfalfa is obtained on the island of Gotland, but the amounts of seeds are limited and there is need for import of alfalfa seed. Seed of root crops is grown mainly in the coastal areas of southern Sweden. Oil crop seed is produced in south and middle Sweden. From the above it is quite clear that Sweden is practically self-sufficient with regard to seeds. Furthermore, these are of high quality, as the rules governing the seed testing and seed certification are very strict and well adhered to by the Government Seed Testing Station in Stockholm and the local seed testing stations. In this field much progress has been made since the Government Seed Testing Station was founded in 1925.

13. Black Fallow and Weed Control

Black fallow was a regular part of the crop rotation in earlier days; now black fallow is no longer common (Fig. 12). At least it has not

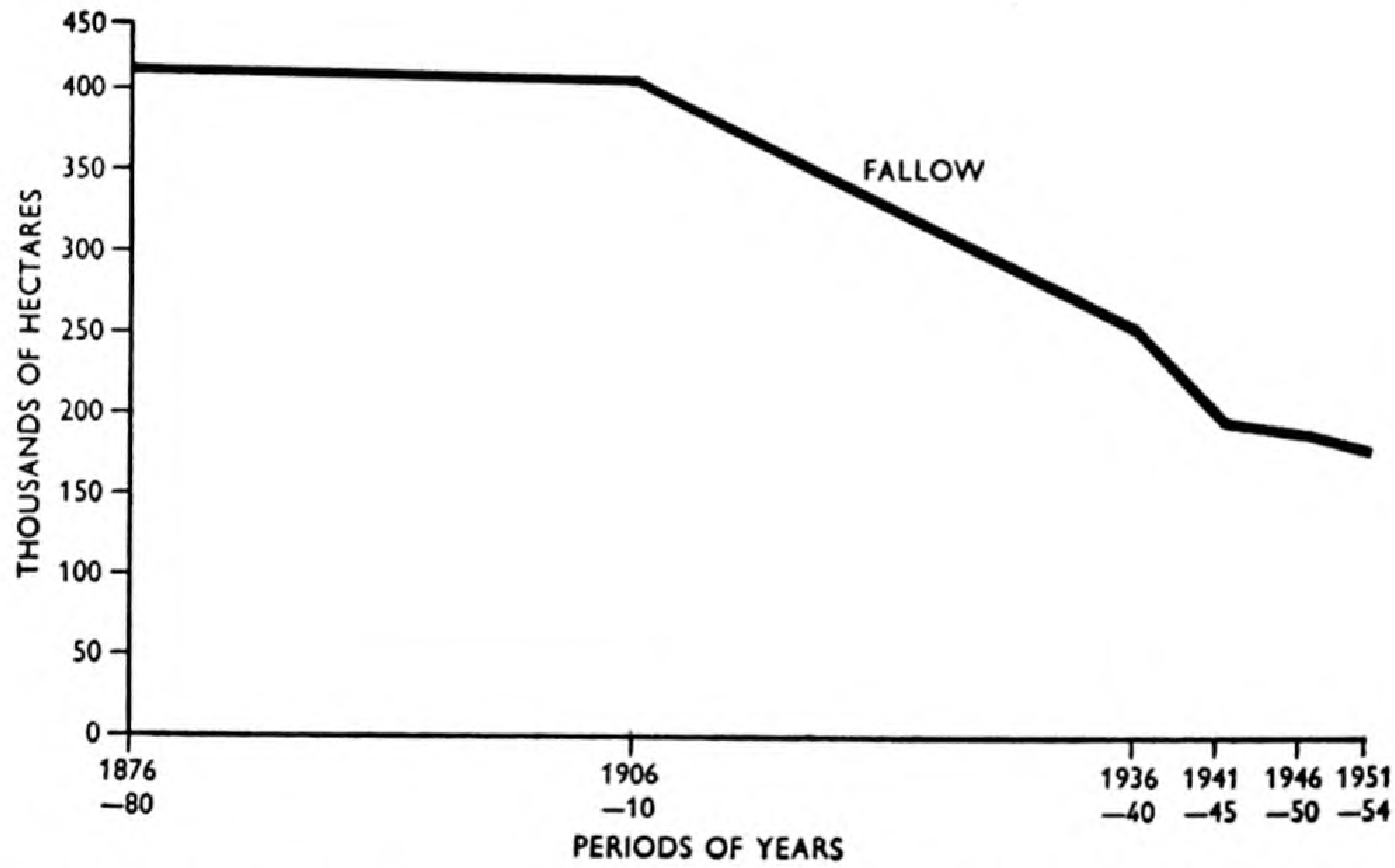

FIG. 12. Acreage of black fallow during the period from 1876 to 1954.

been during the last decade. With the increasing use of fall-sown oil crops some kind of fallow may, however, again become of importance, as the oil crops should preferably be seeded on a well-treated fallow. The figures in Table I indicate that the statements just made may prove to be right ones.

With the intensive type of crop production in Sweden the mechanical treatment against weeds is found mainly in row-seeded crops. It still is an open question if such a treatment is enough in a country with such a short growing season as that of Sweden. Possibly, preference should be given to a combination of the mechanical treatments on a fallow and in a row-seeded crop with the chemical ones in cereals,

flax, etc. This would also tally with the present development and undoubtedly make the Swedish fields cleaner in regard to weeds. In 1953 3249 tons of chemicals were used; this is a 39 per cent increase in relation to the amount used in 1952. In 1948, 958 tons were used and in 1938 only 53 tons. The use of chemical weed killers has thus increased enormously and would indicate that they are accepted as complements to mechanical methods—which is exactly what they should be (Åberg, 1952). Of the chemical weed killers the MCPA-preparations are most common, constituting about two-thirds of the total amounts of weed killers.

III. Summary and Outlook for the Future

The general conditions for crop production in Sweden have been given above together with the developments for a number of different crops. The data undoubtedly show that the old type of crops in the country, i.e., cereals and grasses-legumes, are holding their ground against new crops coming in but also that new ones, i.e., sugar beets and oil crops, have developed into very good complements to the old crops. The data also show that for the old types of crops there have been changes, caused by shifts in the consumers' habits, by changes in export possibilities, by economical and technical developments, etc. These changes have not been anything but adjustments to the requirements of a modern world. They have in many cases been possible as a result of improved methods of growing and improved and better adapted material of different cultivated plants. As things are now, the intensified agriculture will make a still higher production possible in many districts of the country, mainly on lands where improved methods can be applied and an extended use of machines is possible. It might bring with it a need to give up some of the small farms in faraway districts and let the lands on these farms again be planted to forests. Many times this may be advantageous in regard to the rising costs for production of farm products on such lands. But it is very doubtful if the development will bring such an extreme change as has now and then been proposed in the discussions on the future agricultural policy in Sweden, i.e., that a rather large acreage of the present farm lands should go back to forests. Even if the change in northern Sweden from poor six-, seven-, or eight-year-old-leys to good three- or four-year-old leys will mean that a certain acreage is laid free, there is no doubt that it can, for example, be used advantageously for cultivated pastures, which can replace poor natural pastures.

The ever-increasing yields per hectare in Sweden will of course make the country able to produce still more for itself and for export, but

they will also make it possible to bring the products of all crops in Sweden to a still higher quality. Thus the present acreage of cultivated lands in Sweden can be expected to be used for a number of crops giving still better yields than the present ones and giving yields of even better quality. The data in this paper all indicate such a development.

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Mineral Nutrition of Plants as Related to Microbial Activities in Soils[1]

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CONTENTS

I. Introduction

All ramifications of so broad a subject cannot be adequately covered in a brief discussion; but it would be advantageous to explore the activities that may prevail at the root-soil interface, especially emphasizing the probable mechanisms of transfer of nutrient ions across the absorbing membranes of the roots, together with the modifying influences that the microbial population may exert.

Clark (1949) has emphasized the high population of microbes that usually exists in the soil at the root-soil boundary known as the rhizosphere. Under natural conditions it would be unrealistic to study mineral nutrition of plants without taking into consideration the role of the myriads of organisms occurring adjacent to the absorbing roots. Yet, this interrelationship is characterized by a dearth of quantitative data. It is preferable, therefore, first, to consider the current status of information on ion entry into roots when uncomplicated by microbes, and, second to examine the possible and probable modifying influences of microbial activity.

II. Nutrient Ion Accumulation in Roots

The nature of the process of nutrient ion accumulation in roots has been the subject of several recent reviews (Broyer, 1951; Overstreet and Jacobson, 1952; Wadleigh and Richards, 1951). Three processes may be involved in inward ionic transfer across the absorbing membranes of roots: diffusion, exchange, and metabolism. Diffusion may be of two

types: simple and that involving Donnan equilibrium. The magnitude of either type of diffusional process will be conditional upon the concentrations of ions at the surface of the absorbing roots as well as the concentrations of the ions in the absorbing cells in addition to the permeability of the root cell membranes to the diffusate. Exchange adsorption is involved in ionic accumulation by roots, but there is some question regarding the extent to which this process is limiting in ion accumulation. Ion accumulation through metabolic processes is the most intriguing of the three categories mentioned. It is the mechanism by which chemical energy released through catabolism effects the accumulation of ions in the root cells against concentration gradients. To the extent to which one can precisely differentiate between the roles of the three types of processes of ion entry into roots, metabolism probably has the predominant influence under most conditions.

Let us consider the factors that are known to affect the metabolic accumulation of ions by cells capable of absorption. These may be listed as:

1. Supply of metabolite in roots.
   Hoagland and Broyer (1936) provided evidence that absorption of K^+ and NO_3 by barley roots was dependent on the supply of respiratory substrate such as sugar.
2. Oxygen supply.
   Numerous investigations in addition to Steward (1937), Hoagland and Broyer (1936), and Lundegardh (1940) reported that a supply of oxygen to plant roots is essential for absorption of inorganic ions. It is of interest that the level of soil oxygen may modify selectivity of roots with respect to ions absorbed. Hopkins *et al.* (1950) found that decreasing the partial pressure of oxygen in air supply to the root zone was associated with an increase in the concentration of sodium in the tops of tomato, soybean, and tobacco plants; whereas the opposite effect was noted for the concentration of potassium, calcium, and phosphorus.
3. Carbon dioxide accumulation.
   The inhibitory action of carbon dioxide in ion absorption has been studied by Chang and Loomis (1945). They concluded that increasing carbon dioxide content of the air supplied to nutrient cultures may be toxic per se to plants over and above any effect of inadequacy in oxygen supply. Under alkaline soil conditions, increasing partial pressure of carbon dioxide brings about an increase in concentration of the bicarbonate ion in the soil solution. The presence of the bicarbonate ion in the sub-

strate was associated with an abnormally high level of potassium accumulation and a low level of calcium content in the leaves of pear trees (Lindner and Harley, 1944), and bean plants (Wadleigh and Brown, 1952).

4. Supply of nutrient ions.
   Numerous studies in addition to those of Hoagland and Broyer (1936) and Robertson and Wilkins (1948) have shown that metabolically controlled salt accumulation is conditioned by the concentration of ions in the external medium.
5. Level of internal accumulation.
   One would deduce that cells with a relatively low concentration of salt are more effective in displaying metabolically induced salt accumulation than those having a relatively high salt level. Hoagland and Broyer (1936) presented clear-cut evidence that this is so.
6. Competition between ions.
   Antagonism among ions diffusing through a membrane has long been a field of investigation by physiologists. Studies of this type have now evolved into ascertaining degrees of competition among ions for protoplasmic binding sites that effect ion transport across the cytoplasm. Since this is a relatively active field of inquiry at the present time, it will be discussed at some length.
7. Stimulative effects.
   Viets (1944) found that increasing levels of Ca^{++} in the culture solution up to 200 meq. per liter were associated with increasing accumulation of potassium uniformly supplied at 5 meq. per liter. This effect was not observed, however, under conditions that inhibited oxidative metabolism. Caplin and Steward (1948) observed that there was an active principle in coconut milk that stimulated the mature secondary phloem tissue of carrot to active and very rapid growth—conditions favorable to enhanced absorption of nutrient ions.
8. Toxic effects.
   Since salt accumulation by roots is usually dependent on concomitant aerobic respiration, Machlis (1944) proceeded to study the effects of the oxidase inhibitors, cyanide and azide, and of the dehydrogenase inhibitors, iodoacetate and malonate, on the respiration and bromide accumulation by excised barley roots. Cyanide and azide were found to inhibit approximately two-thirds of the respiration and, at the same time, prevent any accumulation of bromide. Machlis suggested that cytochrome

oxidase was the enzyme affected. Iodoacetate and malonate were found to inhibit both respiration and salt accumulation. Malate, succinate, fumarate, and citrate reversed iodoacetate inhibition of both respiration and accumulation of salt and neutralized malonate inhibition of accumulation. This suggested that the citric acid phase of Krebs' cycle was an integral part of the respiratory system essential for salt accumulation.

9. Membrane specificity.
   Specificity in ion absorption is especially evident in the wide range in accumulation of sodium by different species when grown at a given level of sodium supply. Collander (1941) determined sodium content of the herbage of 21 species supplied with 2 meq. of sodium per liter in the culture solution. Very little sodium was found in buckwheat, with the other species ranging up to the very high accumulation of this ion found in *Atriplex hortense*.
10. Temperature.
    Ulrich (1941) showed the concurrence among trends of O_2 consumption, CO_2 evolution, and salt absorption by excised barley roots as affected by temperature. At 5° C., 100 g. of fresh roots consumed 41 ml. of oxygen, produced 36 ml. of CO_2, and accumulated K^+ to a level of 13 meq. per liter of sap during 8 hours. These three effects increased concurrently with increasing temperature and at 35° C. 100 g. of fresh barley roots consumed 246 ml. of oxygen, evolved 247 ml. of CO_2, and accumulated K^+ to 41 meq. per liter of sap for the 8-hour period.
11. Water.
    The role of soil moisture in the mineral nutrition of plants has been reviewed by Wadleigh and Richards (1951). Water in the soil affects ionic accumulation in plants in three ways: (a) by conditioning the availability of nutrient ions; (b) by regulating plant growth processes dependent on soil moisture availability; and (c) by the effects of anaerobiosis resulting from excess water in the soil.

The foregoing factors affecting metabolic ion absorption are interrelated in their effects on the conflux or processes involved. Lundegardh (1940) has developed an intriguing concept pertaining to the mechanism by which chemical energy released through the respiratory process is used in ion accumulation by plant cells. Since this theory has received considerable attention in recent reviews (Broyer, 1951; Robertson, 1951; Burstrom, 1951; Overstreet and Jacobson, 1952) on the min-

eral nutrition of plants, it is well to consider it briefly, even though recent investigations have emphasized its inadequacies.

The Lundegardh hypothesis assumes that the cytochrome systems are an integral part of ionic transfer from the outer cell surface across the cytoplasm into the vacuole. The chain of events from energy release by respiration to inward transfer of cations is set forth briefly as follows: When the hydrogen atom liberated by the dehydrogenase phase of respiration reaches the cytochrome system, the cytochrome picks up the electron and the hydrogen ion is freed to exchange for external cations. The resulting ferrocytochrome effects movement of the electron to the outer cell surface, where the electron is lost via cytochrome oxidase to externally supplied oxygen; and the oxidized ferricytochrome acts as an inward carrier for anions. Robertson and Wilkins (1948) pointed out that if the Lundegardh theory is valid, the maximum rate of anion accumulation in the cell should take place when each electron leaving via the cytochrome system is exchanged for an anion from the external medium. On the assumption that respiration is proceeding by the cytochrome system, all molecular oxygen involved in the process becomes combined as water, and each molecule of oxygen requires four electrons and four hydrogen atoms. Hence, the maximum rate of salt accumulation should be 4 gram moles of monovalent salt accumulated for each gram mole of oxygen used, or salt accumulation/salt respiration = 4. Robertson and Wilkins (1948) studied chloride intake by carrot tissue in relation to respiration and found that the value of the aforementioned ratio tended to approach a value of four if neither the rate of respiration nor the rate of chloride accumulation was limited by the external concentration. These results were confirmatory of the Lundegardh theory.

In a later contribution, Robertson *et al.* (1951) presented evidence that the Lundegardh concept is not adequate to explain the complexities of the mechanism of ion absorption. They found that 2,4-dinitrophenol inhibited the accumulation of KCl by carrot cells while enhancing the rate of respiration. Furthermore, 2,4-dinitrophenol increases the leakage of ions from cells transferred from salt to water. The respiration stimulated by dinitrophenol is sensitive to inhibition by cyanide. Although cyanide inhibits salt accumulation, it apparently does not induce leakage of ions from the cells. On the evidence (Bonner, 1949) that dinitrophenol blocks the transfer of energy-rich phosphate to growth processes, Robertson *et al.* (1951) suggest that the Lundegardh theory requires modification to allow for the participation of energy-rich phosphate.

In their review of the mechanisms on ion absorption by roots, Over-

street and Jacobson (1952) point out that probably the greatest service of the Lundegardh concept has been in showing the very close relationship between salt accumulation and the cytochrome system. Because of the quantitative and qualitative linking of ionic accumulation with cytochrome-mediated respiration, it seems probable that any theory of salt absorption will involve the cytochrome system. They regard the actual identification of the cytochrome-cytochrome oxidase system with the actual ion carrier as premature.

These reviewers emphasize Rosenberg's (1948) thermodynamic treatment of ionic accumulation involving the postulation of ionic donators and acceptors in diverse parts of the system: external substrate—membrane—internal phase. The mechanisms of transport so analyzed are involved in the Lundegardh theory. Nevertheless, Overstreet and Jacobson (1952) point out several objections to this theory, viz.: (1) different rates of absorption of diverse ions with the same charge, (2) unequal rates of absorption of cations and associated anions, and (3) the mutual reciprocal effect of ion pairs. Furthermore, as Epstein (1953) points out, there is now valid evidence for specific binding sites on protoplasm for cations in contrast to the concept that cations move passively through the protoplasm as mere electrovalent companions to the anions that are transferred metabolically. Epstein, by supplying cations on exchange resins, has also accrued unpublished evidence that "salt respiration" is just as much associated with cation accumulation as with anion accumulation.

It is pertinent to consider the current evidence on the importance of cytoplasmic binding sites in ion accumulation. Jacobson and Overstreet (1947) have set forth the properties that must characterize hypothetical compounds or reactive groups that are capable of fixing in plant cells inorganic ions taken from the culture medium in exchange for equivalent ions released by the cells:

"1. The ion fixing compounds must be related to the oxidative metabolism of the plant since there is a parallelism between ion absorption and oxygen tension. Under conditions of arrested metabolic activity such as at low temperature or in solutions in equilibrium with low oxygen tensions, very little or no accumulation takes place in root systems or in a variety of other cells.

"2. The ion fixing compounds in the protoplasm must form compounds with ions such as K^+, Rb^+, Ca^{++}, Br^-, NO_3^-, $SO_4^=$, $HPO_4^=$, and others, in which the ions are held by relatively strong bonds since plants are able to accumulate these mineral nutrients offered at extremely low levels of concentration. Furthermore, plant roots can compete with soil colloids which bind nutrient cations very firmly.

"3. The ion fixing compounds should account not only for the absorption of anions and cations, but also for the very wide range in the absorption of different ions of the same sign. This would presumably require two or more classes of compounds or groups.

"4. Although the ions may be bound quite strongly to the ion fixing complex, the combinations so formed must nevertheless possess a high degree of instability since the evidence is that the ions pass into free solution in the vacuoles. Moreover, it is a familiar fact that in response to injury and death, ions absorbed in cells freely diffuse into the surrounding medium. For example, radioactive K could be completely leached from ether killed barley roots."

Jacobson and Overstreet (1947) studied intake and loss of radioactive strontium and iodide by barley roots to gain some insight into the nature of ion fixation within the plant. Many of the determinations were carried out at 0° C. in order to avoid complications due to longitudinal translocation. Observations on live roots at 0° C. and 25° C. indicated the marked dependence of intake of radioiodide on metabolic activity. There was a marked difference between behavior of iodide and strontium in that the intake of iodide increased by a factor of 7.8 for the 25° C. rise in temperature, whereas intake of strontium increased by a factor of only 1.5. The difference between absorption of iodide and strontium was further emphasized by observations on ether-killed roots. Dead roots showed relatively little intake of iodide at 25° C., whereas they were found to take in more strontium at 25° C. during 15 minutes than live roots. Dead roots were found to release absorbed ions to the external medium much more rapidly and completely than live roots. The data suggest that strontium is held differently in live than in dead roots; but even in living tissue, the exchange curves indicate that no appreciable fraction of strontium or iodide is held in a nonexchangeable form. On the basis of these data, Jacobson and Overstreet (1947) were able to make certain observations on the nature of ion carriers: "(a) The ion carriers are intermediate metabolic products or closely related substances; (b) the carriers are not stable *in vitro;* (c) they undergo chemical alteration in the course of their carrier function; and (d) they probably function as chelated complexes."

Studies on the kinetics and characterization of binding sites for ions in absorbing membranes now constitute a most promising field of inquiry in the mineral nutrition of plants. In order to evaluate the influence of microbial activity on the entry of nutrient ions into plant roots, it would be helpful to consider briefly a few recent observations on the nature of entities in protoplasm capable of binding ions. Roberts and co-workers (Roberts *et al.*, 1949; Roberts and Roberts, 1950; Cowie

et al., 1949) have produced evidence that the binding sites for potassium in *Escherichia coli* are closely associated with carbohydrate metabolism.

Jacobson *et al.* (1950) investigated the competition between K^+ and Ca^{++} and found that although the presence of K^+ reduced the absorption rate of Ca^{++}, the effect of Ca^{++} on K^+ was more complicated. In certain concentration ranges, Ca^{++} depressed absorption of K^+, but at other levels it enhanced entry of K^+. It was concluded that probably a single binding substance serves both Ca^{++} and K^+, but an additional special role must be assigned to Ca^{++} in the absorption process. This is in line with the earlier observations of Viets (1944).

Epstein and Hagen (1952) devised a novel approach to the kinetics of ion binding during absorption by considering the reaction of an ion with the binding entity as analogous to the equilibria between enzyme and substrate. They hypothesize that the absorption involves the formation and breakdown of an intermediate labile complex, MR, of the metal ion, M, with a metabolically produced binding compound or carrier, R. The analysis is essentially identical with the kinetic treatment of enzyme reactions presented by Lineweaver and Burk (1934) for analysis of the equilibria between the substrate, S, the enzyme, E, and the labile complex, ES. In such an analysis, the interfering ions assume the role of inhibitors or alternate substrates.

Epstein and Hagen (1952) concluded from their work as follows:

"It was found that K and Cs interfere competitively with Rb absorption, and it is concluded that these three ions are bound by the same binding sites or reactive centers.

"Except at high Rb or Na concentrations, Na does not interfere competitively with Rb absorptions; that is, is not bound by the same sites. At low Rb concentrations, Na over a wide range of concentrations entirely fails to interfere with Rb absorption. Li is not competitive with regard to the K-Rb-Cs sites; i.e., it is not bound by them. At relatively low concentrations of Rb and Li, Li increases the rate of absorption of Rb.

"The findings are considered to be consistent with the hypothesis and indicate the existence of several distinct binding sites of which one group binds K, Rb, and Cs in preference to Na and Li."

Epstein and Leggett (1954) have studied competition among Sr, Ba, Ca, and Mg for binding sites in metabolic absorption by barley roots. They found that Ca, Sr, and Ba compete for identical binding sites, but that the Mg ion does not compete for these same sites. Furthermore, Epstein (1953) has presented evidence on the absorption of anions indicating that Br and Cl compete for the same binding sites, but the NO_3 ion is noncompetitive on the halide binding.

These recent investigations emphasize the diversity and specificity of labile "ion carriers" or binding sites that undoubtedly occur in the absorbing membranes of plant cells. There is sound evidence that these "carriers" are metabolically energized in the protoplasm and they appear to be the key determinants in mineral nutrient absorption by plant roots.

III. Microbial Activities and Ion Accumulation

The soil microbiologists have accrued information that would aid them in predicting or indicating the manner and extent to which microbial activity may affect or be involved in the eleven previously listed factors conditioning metabolically induced ion absorption by roots. Norman (1951) and Clark (1949) have recently reviewed the influence of soil microorganisms on the availability of mineral nutrients to crop plants. Let us consider briefly, nevertheless, some possible and probable effects that soil microbes may have on these eleven factors.

1. Supply of metabolite in roots.
   Since the population of soil microorganisms is especially intense at the surface of roots, presumably owing to the supply of energy material sloughed off or emanating from the roots, it is conceivable that the supply and quality of metabolite in the root may affect the density of population in the rhizosphere, which, in turn, may affect availability of minerals in the soil. Furthermore, microbial activity under certain conditions, influences the availability of minor elements in the soil (Clark, 1949), which, in turn, may affect chlorophyll formation in the leaves (Brown, 1953) supplying metabolite to the roots.
2. Oxygen supply.
   Microorganisms carry on respiration and may contribute to depleting the oxygen supply under conditions of poor aeration (Norman, 1951). Low oxygen supply will not only affect the metabolism of root cells but will also condition the availability of nitrogen and such minor elements as iron and manganese (Wadleigh and Richards, 1951).
3. Carbon dioxide accumulation.
   Norman (1951) points out that "under optimum conditions in soils well supplied with organic matter, carbon dioxide evolution may attain rates as high as 100 pounds per acre per day, though figures of 20–30 pounds per day are more general." Under poor soil aeration, such activity could contribute to bringing about a level of CO_2 at the root surface that is inhibitive to ion absorption (Chang and Loomis, 1945).

4. Supply of nutrient ions.
   Clark (1949) has reviewed the evidence on this point. The activities of microorganisms can be a major consideration in the supply of nitrogen, phosphorus, sulfur, and minor elements to plants.
5. Level of internal accumulation.
   Soil microbes would have an indirect effect on this point in that they may have affected the supply of nutrients to the plant at an earlier stage of growth, thereby influencing the facility with which the plant effects ion accumulation at the later stage.
6. Competition between ions.
   The production of CO_2 by microbes may effect an increase in hydrogen ion concentration in the soil and thereby alter the relative availability of cations and phosphate. Any effect microbial activity may have on depleting oxygen supply may also have the further effect of modifying any inherent capacity the plant root possesses with respect to selectively excluding sodium (Hopkins *et al.*, 1950).
7. Stimulative effects.
   Schmidt (1951) reviewed the evidence relating the effects of growth-stimulating substances produced by bacteria. Numerous investigators have shown that various growth regulators for higher plants are produced by bacterial synthesis. Substances so produced have been shown to stimulate seed germination and nodule formation on legumes. It is quite possible that certain of these growth regulators could promote metabolically controlled ion absorption.
8. Toxic effects.
   Steinberg (1947) grew tobacco seedlings in aseptic culture in the presence of diffusates of certain common soil bacteria and found that various types of chlorosis developed on the leaves. In a later work, Steinberg (1951) collected samples of soil adjacent to the roots of tobacco plants which were either growing normally or were severely frenched. In six of seven paired samples of rhizosphere soil, higher populations of *Bacillus cereus* were found for the frenching soil than were found in normal soils. Roots of frenched tobacco showed especially large populations of *B. cereus*, with values several times those hitherto reported for normal plant roots. The study indicated a good probability that *B. cereus* has a causal relationship in frenching of tobacco. As Norman (1951) points out, organic acids are a product of bacterial activity under anaerobic conditions. Little is known as

to what effect these acids would have on plant roots, but it is interesting to recall that Machlis (1944) found malonate to be highly inhibitory to root respiration and salt accumulation. There is appreciable evidence (Schreiner, 1923; Bode, 1939; Pickering, 1917) that organic substances produced by anaerobes in waterlogged soils may be specifically toxic to plants.

9. Membrane specificity.
   The nature of the environment cannot change inherent characteristics, but environmental modifications can condition the degree to which heritable specificities may be expressed. In other words, products of microbial metabolism may alter the degree to which the roots of different species of plants give expression to specificity in membrane permeability. However, any comment as to what might occur in this regard would be pure speculation. Schmidt (1947) has reviewed evidence that the presence of mycorrhizae on the roots of certain species (conifers) enhanced the absorption of mineral nutrients.
10. Temperature.
    Jones and Tio (1948) observed "frenching" of tobacco when the soil temperature was maintained at 35° C., but not when held at 21° C. The authors concluded that microorganisms capable of impairing ion availability to the tobacco plants were stimulated by the higher temperature. Sterilized soil did not show the differential response to temperature.
    The definite effect of temperature on the activity of soil microbes is fully recognized, and further comment is superfluous other than to emphasize that the degree to which microorganisms affect mineral nutrition by means previously listed will be conditioned by soil temperature.
11. Water.
    Wadleigh and Richards (1951) briefly reviewed evidence pertaining to the influence of excess soil moisture on microbial activity as related to mineral nutrition of plants. Obviously, such conditions induce anaerobiosis by which toxic organic substances may accumulate, or the availability of minor elements may be changed by a change in the state of oxidation. Thom and Smith (1938) point out that anaerobic decomposition of organic matter in waterlogged soils frequently produces hydrogen sulfide. This substance is very toxic to plant roots.

It should be recognized that the foregoing discussion of possible ways in which soil microbial action may affect metabolic accumulation of

ions by plant roots contains a high degree of speculation. Nevertheless, it is worth while to call attention to these points, since they comprise a fertile field of investigation in the study of soils and soil fertility.

IV. Summary

The evidence and current concepts concerning metabolic accumulation of ions by plant roots are discussed. Eleven factors that affect ion absorption are set forth:

1. Supply of metabolite in root cells.
2. Oxygen supply.
3. Carbon dioxide accumulation.
4. Supply of nutrient ions.
5. Level of internal accumulation of ions.
6. Competition between ions.
7. Stimulative effects.
8. Toxic effects.
9. Membrance specificity.
10. Temperature.
11. Water.

The possible and probable effects of the activities of soil microorganisms on each of these factors are also discussed.

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Improvement of the Sugar Beet in the United States

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CONTENTS

I. Introduction

The sugar beet, source plant of nearly 40 per cent of the world's sugar, is the product of breeding research during the past century. In this respect, it is almost unique among our food plants, since, for the most part, these have come to us from primitive man with their present-day characteristics and uses. The history of sugar from the beet has a span of but little more than two centuries, starting from the discovery, in 1747, that the beet contains sucrose and the finding, about 50 years later, of ways and means for its extraction and crystallization. A chemist, Andreas Sigismund Marggraf (1747), of the Royal Academy of Science in Berlin, proved that the "white mangold," probably Swiss chard, the so-called sugar root (*Sium sisarium* L., a relative of water parsnip), and red mangold or red beet (called by Marggraf *Beta rubra*) all contained a sugar identical with that from sugar cane, thereby putting an end to the belief that sucrose was to be found only in the tropical plant. Marggraf foresaw that a domestic manufacture of sugar was a possibility, saying "This sweet salt, sugar, may be made as well from our plants as from sugarcane." But it was only after his death that his student and successor in the Academy, Franz Karl Achard, began his classic researches on the Runkelrübe—the forage beet—that were to establish the beet as an economic source of sugar. In 1799, King Frederick William III of Prussia made a grant to Achard to capitalize upon his years of investigation. For the first time, the name sugar beet came into use. Lippmann (1925) has given a detailed, factual account of Achard's contribution; Tannenberg (1942) begins his dramatic story of the early struggle between sugar cane and sugar beet with a very complete account of Achard's early researches in the Royal Academy and his experiences at his little sugar beet factory in Silesia.

II. The Development of the Sugar Beet in Europe

1. *Early History*

The story of Achard, universally recognized as the father of the beet sugar industry, and of his little sugar factory built in 1802 at Cunern, near Steinau, in Lower Silesia, is typical of scientific pioneering. Skepti-

cism, obstacles, and disappointments had to be met until, finally, practicality was proved; but neither reward nor recognition in his own time was to come to the discoverer. Achard, working with crude plant material, probably not greatly unlike our mangel-wurzels, developed effective processing methods and, with facile pen and great generosity of spirit, made his discoveries freely known to the world. From this beginning trace all the developments of the beet sugar industry of Germany, France, Austria, and other countries. Agricultural economists point out that the contribution of the sugar beet was not alone the sugar from its roots but the revolutionary effects it brought about in European agriculture, essentially changing farming from a constant cropping with small grains to a system of rotated crops. In a region where corn was not grown, the sugar beet produced this change by supplying through its tops, crowns, and pulp, the feedstuffs necessary to foster the livestock industry. Small grains no longer were the dominant or sole crops grown on the farm, the weediness of fields was overcome, land was manured, areas formerly deemed unfit were brought under cultivation, and levels of soil fertility were raised. More than anyone else concerned in the early developments of the beet as a sugar source, Achard (1803) recognized the paramount importance of the agricultural phases and what the beet could contribute, stressing in his writings the methods of culture, the need of a sound agronomy, and the gains to the farmer. He stressed also the vital necessity of varieties of high quality, and he greatly improved the beets he grew for his factory.

2. *The White Silesian Beet*

The forage beet, or Runkelrübe, from which Achard selected the first sugar beet, was a complex of beet types. Our best information, of course, comes from Achard himself, who describes the main types within the material grown for cattle feed by the farmers around Magdeburg, Germany. These beets had roots with red, yellow, or white flesh and were of various shapes and sizes. They comprised much the range of types we now find in the mangel-wurzels. Achard found that the plants whose roots had white skins, white flesh, and conical shape were richest in sugar and in "pure, sweet juice." After a year or two, he found the best were those plants whose crowns did not have the tendency to grow out of the ground. Achard selected these for culture and for his seed stocks. In time, this type, as grown and maintained by the Barons von Koppy, father and son, whom Achard guided in developing their small factory at Krayn in Silesia, Germany, became the White Silesian beet called by the historian E. von Lippmann (1925) "ancestress of all the sugar beets of the world."

The White Silesian beet had a conformation not unlike our modern sugar beet and probably was much the same in root yield. Its sucrose content averaged about 7 per cent, possibly reaching 10 per cent, according to Schneider (1939). Undoubtedly it was a population of high- and low-sucrose individuals.

In the period from about 1810 to 1850, the small beet factories in France and Germany processed this type of material; many probably operated with lower grade mangel-wurzel types. Vilmorin (1923) describes the Imperial beet bred about 1850 at Grobers near Halle, Germany, by F. Knauer from the White Silesian beet. This variety marked the first notable step in sugar beet improvement, definite enhancement in quality over the White Silesian being shown. Vilmorin (1923) quoted a statement from Louis de Vilmorin that in 1858 the Imperial variety always gave a higher analysis than the others cultivated in France, 13.8 per cent sucrose against 7.5 per cent for French varieties. Ware (1880), in his description of varieties of sugar beet grown in France in 1878, stated that it contains about 13.5 per cent sugar.

3. Vilmorin and the Sugar Beet

In the history of plant breeding the contributions of Louis de Vilmorin are outstanding. Scion of a family of seedsmen, he is famous as the discoverer of the progeny system of breeding—the Vilmorin method of the older textbooks. He pioneered in establishing reference collections of breeding stocks, especially wheats. J. L. de Vilmorin (1923) reviews the work of his grandfather, L. de Vilmorin, in the period 1837 to 1859, when he introduced into sugar beet breeding more accurate methods of selecting for quality, discarding the crude salt-bath flotation method for finding roots of greatest density and substituting for it in 1852 the silver ingot method. In this method, the quality of a beet root was determined by finding the specific gravity of its juice. Fine morsels were rasped from the beet and 7 to 8 ml. of juice pressed out. A silver slug of known volume and weight was weighed when immersed in the juice, giving accurate data for computing the specific gravity of the juice. In 1853, according to Saillard (1922), Vilmorin first used the polariscope in sucrose determinations as an adjunct to the specific gravity technique. By 1860, saccharimetry had become the standard method in selecting sugar beets for breeding purposes.

Such painstaking selection of individual roots would have accomplished only slow improvement had it not been combined with the Vilmorin method of breeding, in which the breeding value of the mother

plant is judged not by its own characteristics but by the performance of its progeny. Hayes and Garber (1921) give an appraisal of the significance to plant breeding of this contribution. Given the tools for precision in selection and an efficient method of breeding, improvement of the sugar beet, beginning in 1860, was rapid and positive. The case can be made that with the screening out of mangel-wurzel types, the sugar beets as bred by Vilmorin at Verrières, France, to replace the White Silesian, and those bred at Kleinwanzleben and elsewhere in Germany to replace the Imperial beet, approached the modern sugar beet in both productiveness and quality.

Schribaux, cited by Vilmorin (1923), shows by a graph that from 1838 to 1868, when morphological selection prevailed, the average richness in sucrose of sugar beets progressed from 8.8 to 10.1 per cent; from 1868 to 1888, to 13.7 per cent; and from 1888 to 1912, to 18.5 per cent. Schneider (1939), in his thorough review of the breeding of sugar beets up to 1939, discusses estimates of improvement in quality over the decades, showing clearly that those based chiefly on statistics of sugar production probably disregard, to a great extent, the enormous improvements in processing techniques that took place as modern chemical methods were developing. Schneider cites other evidences of improvement in sugar beet quality, based on analyses of breeding stocks, to show a steady but moderate improvement. That sugar beet quality has been improved decade by decade by breeding has been challenged by Coons (1936) on the basis of the data Wiley (1898) reported in the agronomic tests with European brands of sugar beet. These results are not strikingly different from what would be obtained today in a similar series of field trials conducted with varieties not resistant to the major endemic diseases. Furthermore, the sucrose percentage values given by Ware (1880) and McMurtrie (1880) as characteristic of the various commercial brands indicate a reasonably high quality.

From this brief review of the early work on sugar beet improvement, it is seen that Achard selected from the forage beet complex the forms that encompassed the potentialities of our modern sugar beet. The breeding work of the nineteenth century screened the population to obtain higher sucrose quality and no doubt high-yielding types. The publications by Vilmorin and Schneider, already cited, cover this work. The job has not gone forward by slow, graded steps decade by decade, but always as sharp responses to discoveries that permitted greater precision in measurement of the attribute in question, whereby the selections were more efficient, and by improvements in the breeding techniques that could capitalize upon the better job of selection.

4. *Sugar Beet Breeding Establishments*

As the sugar beet, beginning about 1830, took on ever-increasing importance in European agriculture, there developed extensive sugar beet breeding establishments to furnish the seed for the beet sugar industry. Such commercial organizations were developed in Germany, Czechoslovakia, Poland, France, and other countries. Breeding research was almost exclusively left to them. Even after the rediscovery of Mendel's laws of heredity had given new impetus to genetics and plant breeding, the sugar beet was not generally a subject of study in European universities and experiment stations. Notable exceptions were the Swedish Breeding Station at Svalöf; the Stazione Sperimentale di Bieticultura at Rovigo, Italy; the Sugar Beet Institute at Kiev, U.S.S.R.; and a few others. The breeding programs of the various commercial seed firms were based upon a progeny system of selecting. Each year, thousands of sugar beet roots were analyzed to serve as the starting point of a progeny selection scheme from which after five to seven years the commercial seed would be obtained. Each year the job was repeated, starting with new roots and ending up with a commercial variety. In the older books on plant breeding, the methods of the European sugar beet breeding establishments were cited as models.

5. *European Sugar Beet Breeding Methods*

European seed companies, in their departments devoted to the sugar beet, have done much painstaking work and have been responsible for notable progress. Procedures have varied, but a considerable number of breeders have sought to follow the method of Vilmorin. Their methods have been described in detail by Coons (1936), and the year-by-year steps from the initial selection of roots to the production of commercial seed diagramed.

The possibilities and the weaknesses of methods which appear to be comparable to the ear-to-row scheme once in vogue in corn improvement may be briefly reviewed. In some of the European schemes, sugar beet roots are selected on the basis of morphology and individual sugar analyses as "heads of families." By the techniques followed, the seed that is produced from the carefully selected mothers is not selfed nor is it the product of controlled matings, but rather the result of polyandry among the mother plants of the seed plot. This comes about because no effective means are used to prevent *inter se* crossing of seed bearers. Furthermore, only plants setting heavy quantities of seed are usable in a scheme that involves extensive progeny appraisal with a portion of the seed, the other portion being planted the same year for production of

roots from which a seed increase can be made if such is desired. In view of the limited set of seed that occurs when sugar beet plants are selfed, the elimination of all plants except those setting the most seed means that, chiefly, out-pollinated progenies are retained. The breeding system, therefore, although ostensibly line breeding, is, in fact, anything but that; whence the name "mother-line breeding" applied to it by Coons (1936).

The agronomic test of the progenies of "Heads of Families" indicates certain progenies as superior to others and as corresponding to one or another direction of breeding—that is, toward high root yield or toward high sucrose percentage. On the basis of these appraisal tests, roots of the progenies that were grown in the companion increase plots are retained for seed production or are rejected. Here again the isolation between mother-line progenies is inadequate; heavy seed yields are obtained from some, and these again are taken. Again the seed lots are divided. A portion is used in agronomic appraisal of the line, the tests often being conducted for several successive years, and the second portion is held in reserve. On the basis of the agronomic appraisal tests, some seed lots are retained for use as the foundation stocks from which the commercial seed is grown; others are rejected. Seed lots that appear to give yield-type plants are put together, and those judged to give high sucrose types are pooled. The seed stocks that on the basis of the appraisal tests would not give plants to be classed in either category form the compromise or so-called normal types (Lathouwers, 1930).

No matter how desirable a commercial seed produced in this way may be, no further use of it is made, the breeding starting afresh every year with new heads of families. It was part of the belief of the old breeders who devised the scheme that direct increase of the commercial seed, in some way not explained, would lead to immediate deterioration.

Thus, the common observation that a sugar beet field, no matter what the brand, presents a conglomeration of types, serves to show that there is little approach to the intensification of certain characters that might be expected in a pedigreed breeding scheme. It also seems clear that the method cannot be expected to give progenies with special characters, such as resistance to disease, unless provision can be made for rigid selection for the desired character. As was shown long ago by Pritchard (1916b), the performance of the variety or brand obtained in this manner may be expected to be the average of its many components and to show little change as, year after year, seed lots follow in the steps of their predecessors. Brewbaker and McGreevy (1938) have discussed critically family and group breeding methods.

III. The Sugar Beet in the United States

1. *Early Attempts to Establish Beet Sugar Industry*

After the sugar beet had gained its important place in European agriculture, there were many attempts to introduce it into the United States. There was an abortive attempt in Philadelphia in 1830, but the first factory was built at Northampton, Massachusetts, in 1838. It ran another year, made 1300 pounds of sugar, then was closed down. Attempts to establish factories in Michigan, Illinois, Wisconsin, and other states all were unsuccessful. The almost incredible effort put forth by the Mormons to establish in 1852 a beet sugar factory near Salt Lake City, Utah, with machinery brought from Liverpool, England, and transported from Fort Leavenworth, Kansas, over the plains by ox trains, is memorialized by Taylor (1944) in his *A Saga of Sugar*. The factory was built and the sugar beets were grown and processed. But lack of chemical know-how gave only sirup as the product. Nevertheless, this brave venture was forerunner of the important industry that about 50 years later was to develop in Utah.

2. *Beet Sugar Industry Becomes Established*

The beet sugar industry in the United States may be said to date from 1870 with the factory at Alvarado, California—a factory that was remodeled in 1879 and essentially rebuilt in 1936, but is still in operation on the original site.

From this period to the present time, numerous factories were started. Many of them operated only a brief period before they were abandoned or moved to another location. A few of these were frank promotional ventures, but mostly they were serious attempts to establish the sugar beet as a part of our agriculture. By 1950, a total of 168 factories had been built; 85 had been removed and 83 were standing, but only 72 were operating. In 1954 there were, in all, 73 factories in 16 states, with a daily slicing capacity of 143,650 tons per day. The history of factories built and factories now operating is illustrative of the difficulties the industry has faced as it won its way in America. Now sugar beets are grown in 21 or 22 states on upwards of 850,000 acres annually, the production of refined sugar being approximately 1.7 million tons. In Canada there are a total of 7 factories, located in Alberta, Manitoba, Ontario, and Quebec. About 100,000 acres of sugar beets are grown annually.

From the start and all through the trial-and-error period when factories were leading almost a gypsy existence, trying to find an area

where they could operate successfully, the sugar beet was grown from seed obtained from European breeding establishments. In spite of early recommendations of the Department of Agriculture and a clear showing, by experiments over a score of years from 1890 on, of the advantage of home-grown varieties and home-grown seed, the industry, dominated by European technologists brought over to run the sugar-making equipment, insisted on imported brands. There is no question that the European seed was capable of giving good crops under conditions comparable to those of Europe, but far too often it was not adapted to conditions encountered in one area or another in the United States. As we shall see, the long-continued use of imported seed was at the bottom of much of the trouble of American factories.

Four major areas are engaged in growing sugar beets, and each of these has its own special conditions of soil and climate. In the humid area, sugar beets are grown in Michigan, Ohio, Wisconsin, Illinois, eastern North Dakota, Minnesota, Iowa, and eastern Nebraska. The soils used are clays or heavy loams; the crop depends on natural rainfall which is frequently heavy in the spring months and adequate in most years in the growing season for good crop production. In the Midwest, particularly in Colorado, western Nebraska, Kansas, western North Dakota, South Dakota, Wyoming, and eastern Montana, sugar beets are grown on heavy soils that are alkaline in reaction; rainfall in spring is fairly frequent but scanty; and there are occasional summer rains. This rainfall needs to be supplemented by irrigation and frequently the crops are irrigated up, since the spring rains do not wet the soils deeply enough. In the intermountain area—Utah, Idaho, Montana, eastern Oregon, and Washington—agriculture is confined to sedimentary, valley soils that can be reached by irrigation water, since rainfall is inadequate to produce the crop. On the Pacific coast, in California, the sugar beet crop is grown on a wide range of soils and under irrigation, the water coming either from streams or wells. The climate allows the crop to be grown either as a summer or a winter crop.

3. *The Sugar Beet Threatened by Disease and Insect Attack*

Sugar beet culture is limited to acreages within economical transportation distance of a beet sugar factory equipped to carry on the highly technical process of sugar manufacture. This and other factors have tended towards intensification of sugar beet culture; accordingly, problems associated with intensified agriculture, especially serious diseases, have been encountered. In each of the major districts, plant diseases have been responsible for serious crop failures and, as the industry was becoming established, were the chief causes of the lack of success of one

factory after another, bringing about the frequent moves from one place to another as stable crop production was sought. Thus, the humid area had a long period of persistently low yields because of black root (*Aphanomyces cochlioides* Drechs. and other fungi) (Fig. 1) and leaf spot (*Cercospora beticola* Sacc.). Abundant rainfall, which should have

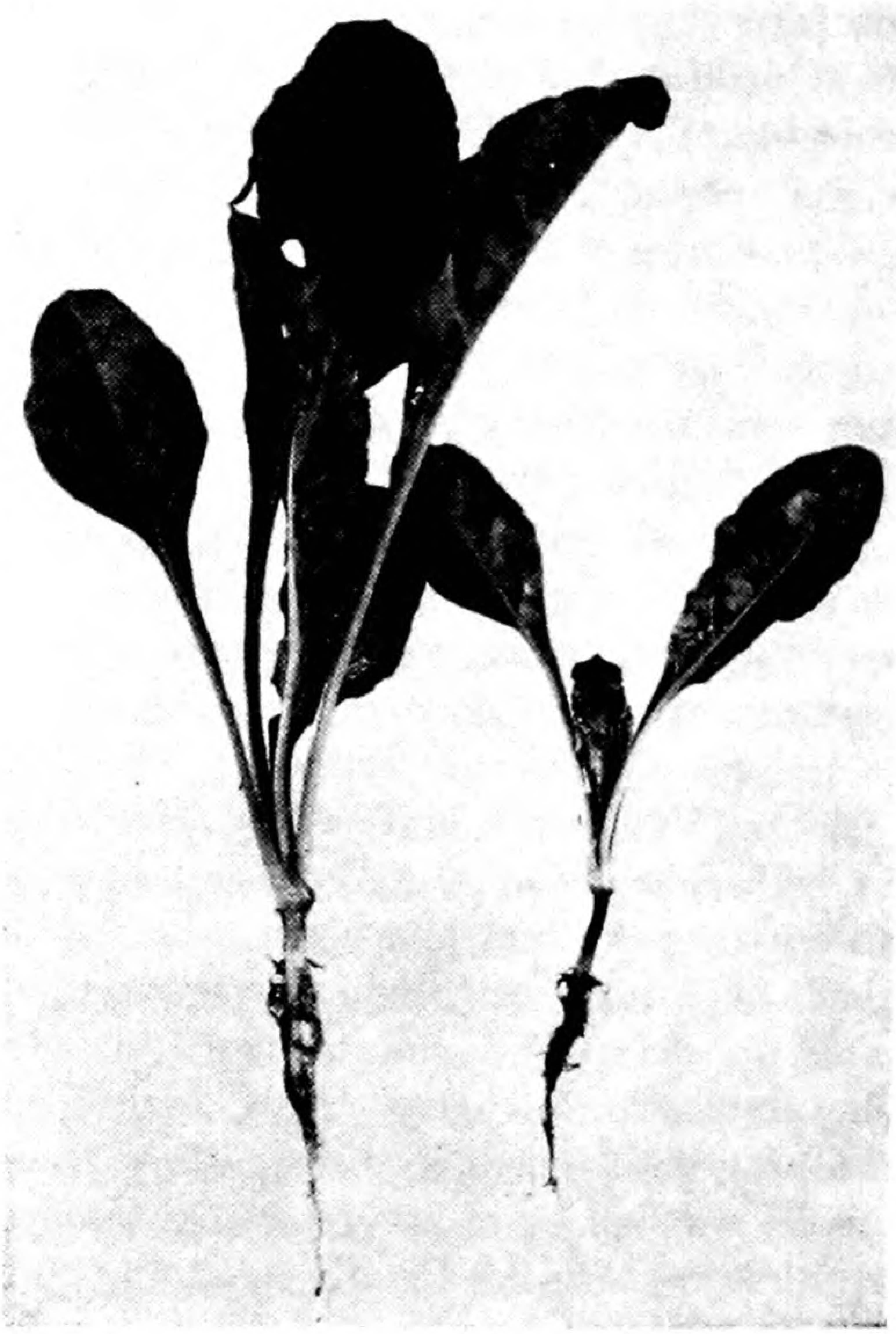


FIG. 1. Black root of sugar beet. The taproot of the sugar beet plant at the right is blackened and its lateral roots are killed by the water mold, *Aphanomyces cochlioides*. Some measure of the stunting of growth is afforded by comparison with the healthy plant of the same age on the left. Frequently, affected plants die. (Photograph by J. E. Kotila.)

meant bumper crops, brought about poor stands, low tonnages, and low sugars (Coons, 1953b). As a consequence, factories were unable to contract adequate acreages in their vicinities.

The Midwest has had serious losses from leaf spot, and, even now, certain states are experiencing outbreaks of curly top. In the period 1920 to 1940, serious leaf spot epidemics occurred frequently in many districts, particularly in Iowa, Nebraska, Kansas, and eastern Colorado.

Often the disease so reduced yield and quality as to make the sugar beet crop unprofitable to the farmer as well as the factory, and the industry was brought to a low ebb.

In the intermountain area and in California, curly top, a virus disease that was studied so intensively by Carsner (Carsner and Stahl, 1924), was, over the years, the most serious menace to the sugar beet industry, almost bringing about the abandonment of the sugar beet culture west of the Rocky Mountains. In its capacity for producing injury, curly top ranks with the most destructive plant disease (Fig. 2).

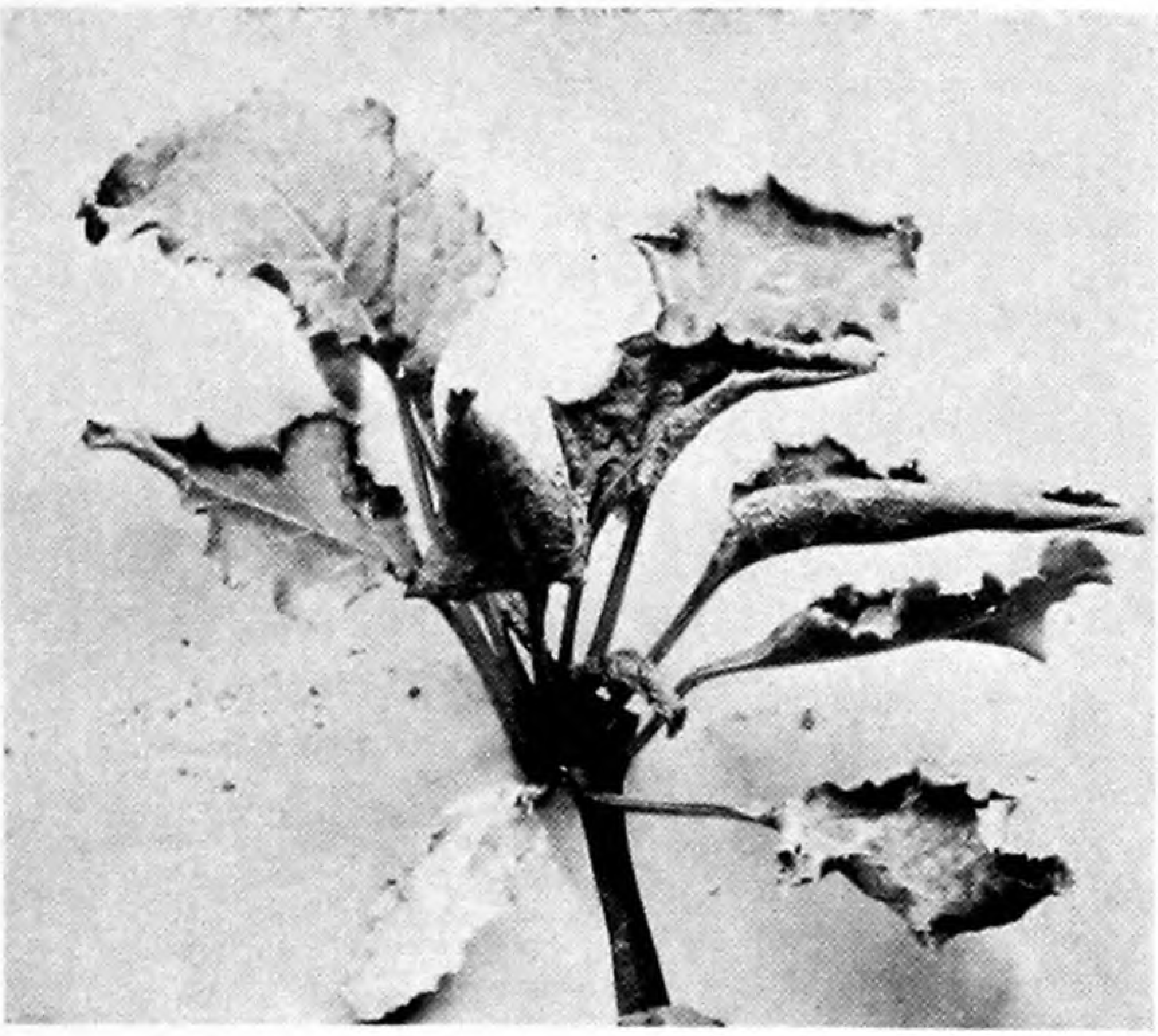


FIG. 2. Sugar beet curly top. Affected plants are stunted, their leaves upcurled, and the veinlets in the leaves are enlarged and distorted. A diseased plant, such as shown, will make little or no growth throughout the entire season.

The virus occurring in range plants is brought to sugar beet fields by the beet leafhopper, *Circulifer tenellus* (Bak.). Douglass and Cook (1954) have published a résumé of the life history of the beet leafhopper. This leafhopper prefers dry climatic conditions. It breeds on mustards (Tumblemustard, *Sisymbrium altissimum* L. and Flixweed tansymustard, *Descurainia sophia* (L.) Webb), Russian thistle (*Salsola pestifer* A. Nels.), filaree or alfilaria (*Erodium spp.*), and other weeds that have invaded western range lands deteriorated as a consequence of overgrazing. These weeds are hosts of the curly top virus.

The vicious cycle of range deterioration, weed invasion, beet leafhopper increase, and curly top epidemics has been outlined by Piemeisal *et al.* (1951). When the vegetation of the range lands becomes dry in

early spring, swarms of beet leafhoppers, some of them viruliferous, move into the irrigated valleys. Here the insects feed on the young sugar beet plants, infecting some of them with curly top virus picked up from the weed host plants. Each infected sugar beet in the field becomes a disease center where the insects breed and where nonviruliferous beet leafhoppers become infectious, and thus they spread the virus. In years of high beet leafhopper populations, not a plant in a sugar beet field escapes infection. Before the development of varieties resistant to curly top, early-infested fields were, in a few weeks, almost a total loss. Thousands of acres around a factory would be abandoned, and the factory would have either no run at all or a very short, unprofitable one.

The European varieties grown had no resistance to the diseases that wrought havoc to American beet crops. Leaf spot and black root occur in central Europe only sporadically and in mild form. Curly top does not occur. Obviously, varieties as bred in Europe could not be expected to exhibit resistance to these diseases.

Such was the situation in the United States at the close of World War I. The industry had had a precarious existence during the war and was hampered by shortages of sugar beet seed. All through the formative years, the industry had elected to depend upon imported seed. The attempts to produce seed in the United States in 1917, 1918, and 1919 were notably too little and too late. They were dropped at the close of World War I. Then, in the next decade, leaf spot, black root, and curly top brought disaster to many companies.

IV. Breeding for Disease Resistance

In 1925, direct attack on curly top and leaf spot by disease-resistance breeding was started in the Bureau of Plant Industry of the United States Department of Agriculture. The wild relatives of the sugar beet were collected in Europe; selection work was started with commercial sugar beet varieties and with breeders' strains at field stations where severe exposures to these diseases could be expected each year.

1. *Resistance to Curly Top*[1]

The first result of this breeding program was the production of a variety of sugar beets having some resistance to curly top. Carsner and Pack (Carsner *et al.*, 1933) selected vigorous roots from a number of

[1] The breeding of curly-top–resistant varieties was conducted by Eubanks Carsner, D. A. Pack, F. V. Owen, F. A. Abegg, and A. M. Murphy, assisted in the agronomic testing by A. W. Skuderna, C. E. Cormany, Bion Tolman, J. O. Culbertson, H. A. Elcock, and Charles Price. The investigations were cooperative with the California, Colorado, Idaho, New Mexico, Utah, and Oregon Agricultural Experiment Stations and the western beet sugar companies.

Utah fields in which curly top was causing a decimating loss. Roots that appeared to be definitely better than the general run of the field were stored over winter and planted in a seed plot with other roots grown from similar selections that had been made earlier by commercial companies. A total of 70 to 100 pounds of seed was produced in 1929. The first test of this seed—later to be designated US 1—was made in 1930

FIG. 3. The initial test of US 1 sugar beet variety at Castleford, Idaho, in 1930. Curly top exposure was severe, almost eliminating susceptible sorts. Plot 1703, left foreground (to the right in front of the man), consists of four rows of US 1. Plot 1704, the four rows to the right, is a nonresistant European brand. In the background, other plots of US 1 and other curly-top-resistant varieties appear as green "islands." (Agronomic test by C. E. Cormany; photographed September 19, 1930 by E. Carsner.)

under conditions of heavy curly top exposure (Fig. 3). As the photograph indicates, and in comparison with later achievements, the showing made by the variety was not impressive. But the situation of the beet sugar factories, brought about by curly top, was so desperate that, with this evidence of some superiority in US 1 over the European types, steps were immediately taken to make a seed increase from the unused seed stock as a source of a curly-top-resistant variety. Details of the increase and the subsequent multiplications have been given by Coons

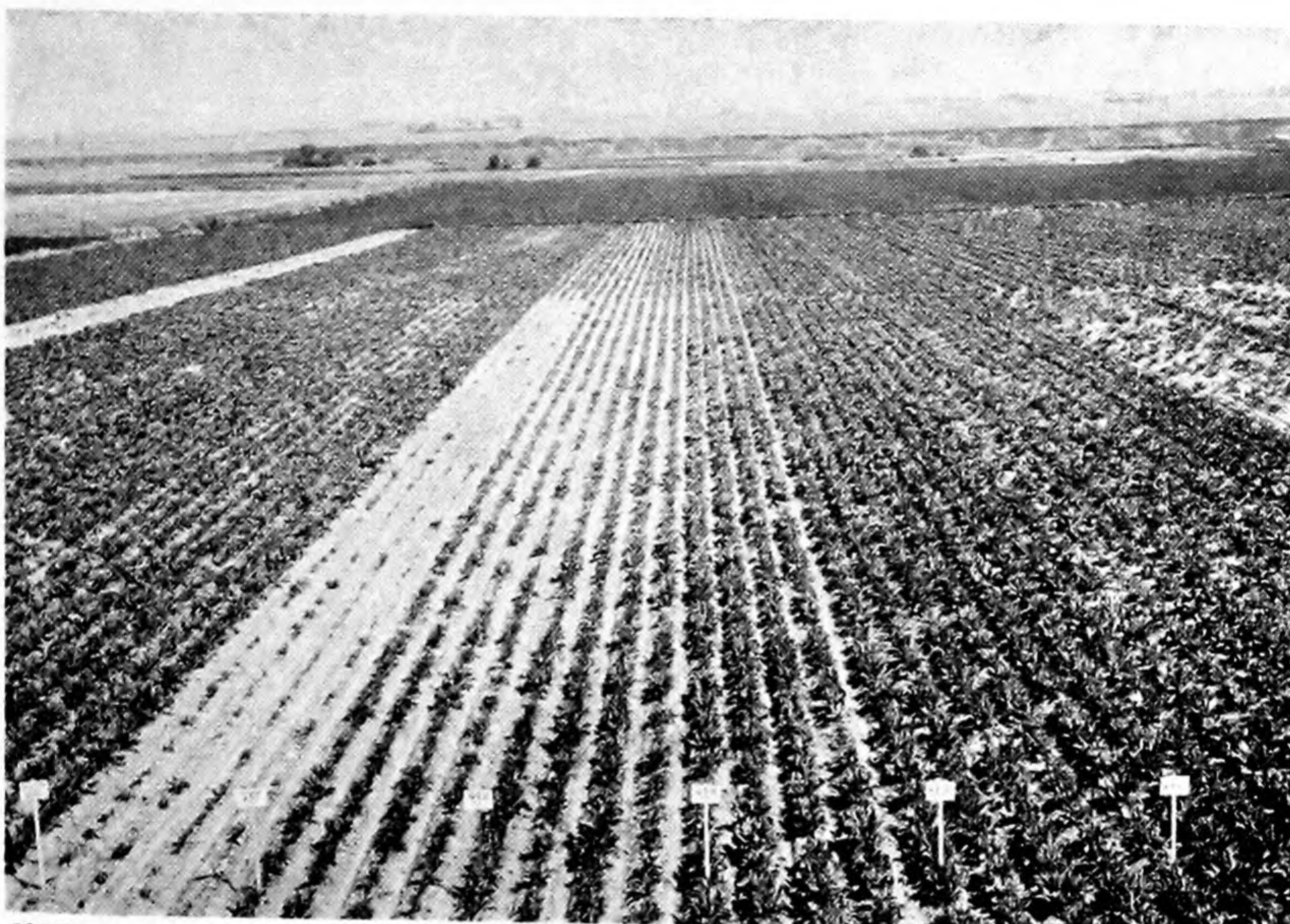
(1936). In the summer of 1932, 22,000 pounds of seed were harvested; in 1933, beet sugar companies grew 200 acres of trial plantings of US 1 in Idaho, Utah, and California. More than 800,000 pounds of seed were produced in 1933, permitting over 35,000 acres to be planted for sugar production in 1934. In 1935, nearly 103,000 acres were planted with the new variety.

US 1 was successful under mild curly top exposures. About one-fourth of the population within the variety was resistant enough to produce fair-sized roots in spite of curly top. The other plants ranged in disease reaction from extreme susceptibility to mediocre resistance. The performance of US 1, however, in comparison with the almost complete failure of the European brands when affected by curly top, made the new variety outstanding. In 32 grower-test plantings in 1931, with curly top injury ranging from moderate to severe, US 1 averaged 5.5 tons better than the susceptible European brands.

The results with US 1 had far-reaching effects. Previously, the attitude of sugar beet breeders had been rather pessimistic as to the possibilities of incorporating in sugar beets the factors for disease resistance. In these experiments, genes for resistance to a virus disease were shown to be present within the sugar beet complex and, by mass selection under severe curly top exposures, were segregated. In contrast to the European practice in which a commercial variety of beets is never given another increase, the original stock of seed of US 1 was multiplied by repeated direct increases *without selection*, and no loss of vigor, no change of resistance, and no change in other attributes that could be measured statistically took place so long as the full population participated in the seed production. Of great significance for the American economy was the acceptance by the sugar beet industry of its need for varieties adapted to its beet-growing districts and its responsibility for producing seed—a marked reversal from the former insistence upon almost exclusive utilization of European seed. A domestic sugar beet seed enterprise was established to bring to farmers the seed of US 1 and the other curly-top–resistant varieties that were soon to follow. Fortunately, in concomitant researches on methods of sugar beet seed production, carried out as a federal-state cooperation with the New Mexico Agricultural Experiment Station, Overpeck (1928) had developed the field overwintering method of seed production. In this method, plantings made in early fall were left to overwinter in the field, the seed being harvested by machine the following summer. It replaced the expensive European method of producing seed from stecklings. The new variety, US 1, was the first commercial variety increased by this method. The sugar beet seed enterprise that was launched to produce the curly-top–

resistant variety grew rapidly. Its contribution in the World War II crisis has been described by Coons (1943). Our entire sugar beet industry now uses domestically grown seed of adapted varieties, importation of sugar beet seed being completely discontinued.

The first curly-top–resistant variety was quickly replaced by US 34 and US 33, produced from the reselections made by Owen and Abegg (Anonymous, 1936) in fields of US 1 severely injured by curly top



Old Type Original U.S. 1 U.S. 33 U.S. 12 U.S. 22 Improved U.S. 22

FIG. 4. The susceptible European variety R and G Old Type is shown at the left, in a four-row strip; then follows US 1, the first curly-top–resistant variety, and the various improvements up to the second release of US 22. In the background is the canyon of the Snake River at Buhl, Idaho.

in 1931. Both varieties were more resistant to curly top than the parent variety, the percentage of resistant individuals in the population having been increased from about 25 per cent to 40 or 50 per cent. In turn, US 12 and US 22 were reselected by Owen and Abegg (Owen *et al.*, 1939) from the curly-top–resistant breeding material comprising the original stocks that had gone into US 1. Under conditions of moderate exposure to curly top, it appeared that in US 12 about 75 per cent of the plants were resistant; whereas, with US 22, introduced in 1942, about 85 to 90 per cent of the plants showed a very high degree of resistance.

US 22 has been repeatedly selected by Albert Murphy near Twin Falls, Idaho. By midsummer field plantings made at right angles to earlier infected strips, Murphy (1942) has been able to produce curly top exposures with a degree of severity far surpassing that which growers experience in March, April, or early May plantings. After a genotype has survived the severe curly top exposure to which these test plantings are subjected, there is little likelihood that it will be seriously injured in farmers' plantings. Sugar beet growers in Utah and Idaho are using extensively the third reselection (US 22/3), and this variety is also used to a considerable extent in late March and early April plantings in California. The degree of curly top resistance obtained by the repeated mass selections is indeed remarkable (Fig. 4). In the areas where curly top was once so serious, the threat of crop failure from curly top has been removed. In years of curly top epidemic, some depression of crop yield still occurs. In extreme instances, growers may sustain a loss of as much as 5 tons of sugar beets per acre, but when cultural conditions are optimum and irrigation water adequate, yields of 30 tons of sugar beets per acre have been obtained in spite of heavy beet leafhopper infestation. Good yields are obtained year after year in districts where European varieties once had failed completely. The industry has been able to re-enter a number of districts from which it was once driven by curly top. A successful factory now stands at Toppenish, Washington, on the foundation of one that was closed down after a brief run, eventually to be torn down—all because of curly top.

2. *Cercospora Leaf Spot*[2]

a. Resistant Inbreds. In most of the sugar beet districts east of the Rocky Mountains, especially in Colorado, Nebraska, and the Great Lakes region, the beet sugar industry had in *Cercospora* leaf spot a counterpart to curly top in the Far West. When climatic conditions favored the development of the fungus, epidemics of leaf spot occurred. Ironically enough, in the irrigated regions of limited water supply, these were the seasons in which, without diseases, the rainfall would have given high yields of sugar beets. In years when rains were frequent in the first half of the season, the foliage of the sugar beet often blighted several times, each new growth of leaves being at the expense of root

[2] The breeding of leaf-spot–resistant varieties was by a team consisting of G. H. Coons, Dewey Stewart, J. O. Gaskill, F. G. Larmer, and H. W. Bockstahler, assisted in the agronomic testing by J. G. Lill, G. W. Deming, S. B. Nuckols, J. O. Culbertson, R. W. Henderson, O. E. Reece, and G. J. Hogaboam. The investigations were cooperative with the Colorado, Michigan, Minnesota, and New Mexico Agricultural Experiment Stations and beet sugar companies operating east of the Rocky Mountains.

growth and stored sugar (Fig. 5). In the period 1915 to 1940, blight years recurred frequently, and in some districts the growing of sugar beets was given up.

Mass selection, so effective with curly top, did not work with leaf spot. The nature of leaf spot is such that in blighted fields resistant

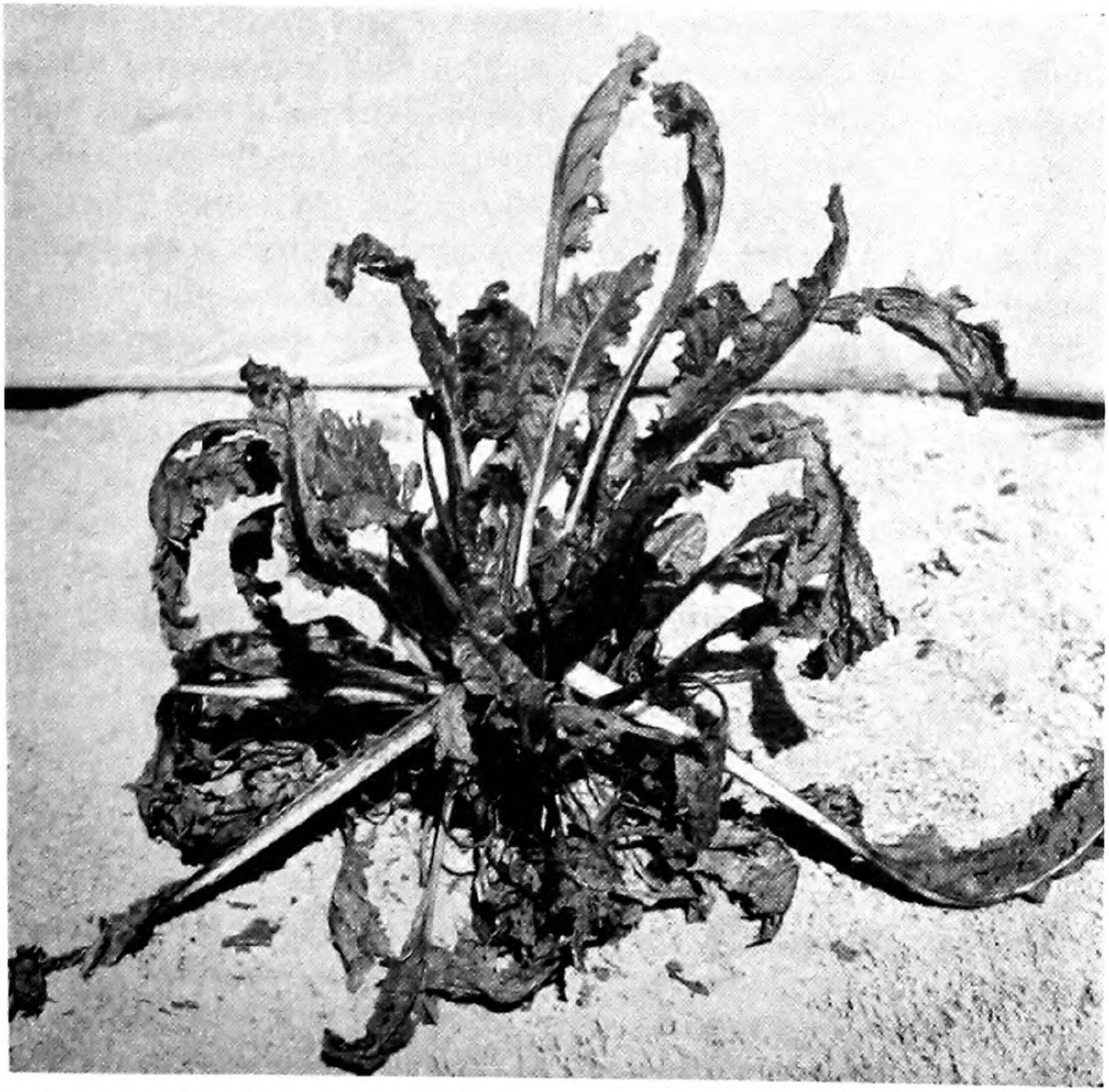


FIG. 5. Sugar beet leaf spot—blighting stage. The dried leaves in the outer whorls that appear as if burned will be replaced by new growth of inner leaves, all at expense of root growth and sugar storage.

individuals cannot readily be detected. As the beet leaves mature, they become more subject to fungus attack, making the recognition of potentially valuable individuals most difficult. When the federal project of breeding for leaf spot resistance was started in 1925, Coons, Stewart, and their colleagues had available to them for experiments at Rocky Ford, Colorado, 200 strains of sugar beet bred by W. W. Tracy, Jr., at Fort Collins, Colorado. Using the Pritchard (1916b) material and certain commercial varieties as starting points, Tracy had, since 1915,

been engaged in isolating as many morphological types of sugar beet as possible. Tracy depended chiefly on group increases of carefully rogued material, but some strains had been obtained by a number of successive selfings. From the 200 strains tested under severe leaf spot conditions in Rocky Ford, Colorado, in 1925, 14 were found more resistant than the others. They remained relatively green, whereas the bulk of the other strains blighted severely. The same strains were found to be outstanding in resistance to leaf spot at Fort Collins, where an attack of the disease also occurred. A study of the pedigree of the strains marked as resistant showed that almost without exception the resistant ones were the product of two or more selfings prior to a final grouping of morphologically similar roots of a progeny to augment seed quantities. From this experiment it was immediately evident that selection, along with continued inbreeding and progeny testing, would be effective in concentrating and stabilizing factors within a strain. Such work has been carried out with the Tracy and other strains by the leaf spot resistance breeding team, as discussed by Coons (1953a, b). The inbreds rapidly became stabilized for the characters governing resistance, but as inbreeding proceeded, there frequently was a definite loss of vigor. As will be discussed in more detail later, hybrids between two relatively nonvigorous inbreds were found in 1932 to show strong heterosis (Coons, 1936; Stewart *et al.*, 1940). Breeding for leaf spot resistance resolved itself into the job of producing as many distinct, leaf-spot–resistant inbreds as possible, then finding, by a series of matings, those pairs that would give a strong heterosis response, satisfactory resistance being maintained.

b. Resistant Varieties. A number of leaf-spot–resistant varieties have been introduced, each representing an improvement in resistance and in productivity over its predecessor. US 217 (Coons, 1936), a synthetic variety, was introduced in 1937 and grown to a limited extent in Michigan. It was replaced by US 200 × 215 in 1940 (Coons and Stewart, 1940). This variety was made by pooling the seed of two leaf-spot–resistant inbreds, US 200 and US 215, and using the mixture as a planting stock for seed production. The variety consisted, therefore, of the hybrid and the sibs of the parent variety. It was ready for introduction in 1939 when the European war cut off supplies of foreign-grown sugar beet seed and forced American industry to move 100 per cent into domestic seed production. US 200 × 215 was entirely satisfactory as a replacement for the European varieties and, when leaf spot was a factor, undoubtedly was greatly superior.

By continued breeding, new leaf-spot–resistant varieties have been developed—notably US 215 × 216, as bred by Coons *et al.* (1941)—

which, in its current phase, is designated as the third release of the hybrid, *i.e.*, US 215 × 216/3. Without leaf spot, this variety in comparative tests is equivalent in sugar production to the European varieties previously grown. Under exposure to leaf spot, it is significantly better than the susceptible European types.

Other introductions of leaf-spot–resistant varieties have been made, including the US 216 × 226 and US 225 × 226. These varieties, in a series of comparative tests, showed superior root yields to the US 215 × 216/3 and maintained the high sucrose percentage characteristic of the latter. In production of all three of these hybrid varieties, utilization was made of the male-sterility factor discussed later. By a series of backcrossings, male-sterile equivalents of US 216 and of US 225 had been produced. Seed stocks of US 216 were available which gave plants showing about 70 per cent male-sterile individuals. US 225 male-sterile (MS) equivalents, in which male-sterility occurred in about 90 per cent of the seed stalks, were available. In the production 215 × 216/3, the seed of the US 216 MS was mixed with seed of US 215 as a means of promoting hybridization and reduction of the sib portions of the population. A similar method was used in producing US 216 × 226. In the production of seed of US 225 × US 226, the seed of pollen-fertile US 226 was planted in a series of strips in the seed field, the major portions of the field being planted with the male-sterile phase of US 225. Presumptively, a high percentage of the seed from the US 225 portions of the field would be hybrid, but it must be recognized that the presence of pollen-fertile plants of US 225 within the main field brought about an appreciable amount of self-pollination.

Comparisons of other leaf-spot–resistant varieties, in which male-sterile equivalents were utilized to increase the percentages of hybrids in the populations, using the European variety as a check, indicate that in these hybrids definite gains in root yields are obtained, leaf spot resistance and high sucrose percentages being maintained. The hybrid variety obtained by taking the commercial seed exclusively from the male-sterile plants showed significant gains over US 215 × 216/3, averaging nearly 10 per cent (Coons *et al.*, 1954). Skuderna and Doxtator (1942) also have given an appraisal of the contributions of leaf-spot–resistant varieties to sugar beet production in southeastern Colorado.

A number of leaf-spot–resistant varieties have been produced by breeding research of beet sugar companies to supply the requirements of their respective districts—notably by Brewbaker and his associates, of the Great Western Sugar Company (Brewbaker *et al.*, 1950), who have introduced GW 59, moderately leaf spot resistant, and GW 304 and

GW 359, both highly leaf spot resistant; by Doxtator (1940) of the American Crystal Sugar Company, who has introduced a series of leaf-spot–resistant varieties under the general designation of AMERICAN I; and by C. E. Cormany and his associates (Peterson and Cormany, 1952), of the Holly Sugar Corporation, who have introduced leaf-spot–resistant varieties under the general designation of MIDWEST.

c. New Sources of Resistance. Italian varieties, CESENA, MEZZANO 71, and ROVIGO 581, have proved to be other excellent sources of leaf spot resistance. These varieties trace to the classic work on sugar beet breeding begun in 1910 by Munerati (1920) at the Stazione Sperimentale di Bieticultura, Rovigo, Italy. Among his many investigations, Munerati studied *Beta maritima* collected along the estuaries of the Po River and made hybridizations of the perennial types with sugar beet. From these matings and by repeated selections, Munerati (1932) obtained sugar beet types that were characterized by a high degree of leaf spot resistance and by high sucrose. These plants, however, as seen by one of us in 1925, had not been freed from certain undesirable characteristics derived from the *B. maritima* parent—notably, the tendency to be multicrowned and to have sprangled roots, especially lateral roots emerging from the taproot at about a 90-degree angle. By 1935, Munerati had greatly improved his breeding stocks and furnished his American colleagues his variety R 581 which, although not fully comparable with sugar beets in root or crown conformation, was extremely resistant to *Cercospora* leaf spot and high in sucrose. In a personal communication in 1935, Munerati stated that he turned over his leaf-spot–resistant stocks to sugar beet breeders at the commercial seed stations located at Cesena and Mezzano, Italy, where the Munerati strains, by further selections and by combinations with other breeding material, became commercial varieties bearing names of the respective stations. The Italian varieties tested in the United States were high-sucrose types with high leaf spot resistance. Cesena contributed leaf spot resistance to GW 304 and GW 359, and federal workers utilized Mezzano 71 in the breeding of US 201, a strain that has shown a new level of resistance among sugar beets in this country.

3. *Downy Mildew and Rust Resistance, Nonbolting Tendency, Combined with Curly Top Resistance*

The curly-top–resistant varieties, US 1, US 33, US 34, US 12, and US 22, only partially met the needs of California sugar beet districts, since their use was limited to plantings of sugar beets made in late March or April. If planted in late fall or winter months, these varieties produced a very high percentage of seed stalks in the first or vegetative

year—a very objectionable and wasteful feature. In sharp contrast to the easy bolting characteristics of these varieties was the nonbolting of US 15.[3] This variety had been selected in 1927 in cooperative work with the New Mexico Agricultural Experiment Station (Coons *et al.*, 1950). Plants resistant to curly top were selected from the high-sucrose European variety, R & G Pioneer. Of the 14 roots selected, only 3 produced seed. The progeny of these roots was noted as showing curly top resistance, and reselections were made; multiplication of the seed

FIG. 6. US 15 in a cooperative variety test at State College, New Mexico. Curly top exposure was severe enough to eliminate susceptible plants. Row 277a is US 15; adjacent rows are planted with less resistant selections. (Photographed October 2, 1930, by H. A. Elcock.)

thus obtained was made in 1930 (Fig. 6). The variety was about to be discarded because of its susceptibility to *Cercospora* leaf spot in plantings made at Fort Collins, Colorado, when its extremely low bolting tendency was discovered by C. A. Lavis and F. G. Larmer in a series of cooperative tests conducted at Davis, California. Here a number of varieties were planted in October and November to find types that

[3] The breeding of US 15 was by a team consisting of G. H. Coons, Dewey Stewart, H. A. Elcock, F. G. Larmer, J. C. Overpeck, C. A. Lavis, and Charles Price. The investigations have been conducted in cooperation with the Colorado, California, and New Mexico Agricultural Experiment Stations and with beet sugar companies operating in California.

would not bolt when subjected to fairly cold weather in late fall or winter in California. In these tests, US 33 and other curly-top–resistant introductions had about 40 to 50 per cent of their populations producing seed stalks and European varieties bolted 10 to 20 per cent, but US 15 under these conditions bolted less than 1 per cent. The variety was also found to be relatively resistant to downy mildew (*Peronospora schachtii* Fckl.) and to rust (*Uromyces betae* (Pers.) Lev.)—both serious diseases in California coastal districts.

US 15 became the variety grown almost exclusively in winter plantings of sugar beets in southern and central California, but its greatest achievement was to make possible sugar beet culture in the vast Imperial Valley of California. Here the growing seasons for sugar beets are reversed, the seed being planted in September and October and the crop grown over winter for harvest in May and June (Coons, 1941). With ordinary sugar beet varieties, such a planting schedule cannot be followed, because the onset of fairly cool weather shortly after the seedlings emerge and the continued cold weather of November and December give conditions that bring about abundant bolting, the sugar beet plants changing from the vegetative to the fruiting phase. When extensive trial plantings were being made in the fall of 1937 with US 33 and other varieties, to determine whether sugar beet culture could be carried on in the Imperial Valley, the excessive bolting that occurred in April and May with these types caused such difficulties in harvest and so reduced yields that the proposal to grow sugar beets in the Imperial Valley was about to be written off as a failure, when the nonbolting characteristics of US 15, as seen in tests at the Meloland Substation of the California Agricultural Experiment Station, El Centro, California, saved the day. Concurrently, with the first trial plantings of sugar beets, Charles Price of the Sugar Crops Section, Agricultural Research Service, was conducting variety tests in cooperation with the Meloland Station. Here it was found that US 15 planted in late September and early October was free from bolting, whereas other varieties bolted 50 per cent or more. The industry therefore turned to US 15 as the variety adapted to the Imperial Valley, and it was grown there almost exclusively for over a decade. The Imperial Valley may have a light exposure to curly top; hence for this region US 15 is well adapted. For many years, over 30,000 acres of sugar beets were grown for shipment to factories located outside the valley, average performances over the years being not far from 18 tons per acre with 18 per cent sucrose. In 1948, a $7,000,000 factory was built at Carlton, near Brawley, to process the Imperial Valley sugar beets.

After a ten-year period of dominance, US 15 was replaced by an-

other nonbolting variety, US 56, bred in California by Price *et al.* (1948). This variety, by its superior curly top resistance, was better than US 15 whenever curly top was serious. In its turn, and after four years of use by growers, US 56 is being replaced by a variety bred by McFarlane and Price (1952), US 75, which manifests a high curly top resistance and a high resistance to downy mildew. Its curly top resistance about equals that of US 22/3.

US 15, US 56, and US 75 illustrate the possibility of combining within one variety factors for resistance to several diseases, as well as the genes for desirable physiological characters. Starting with a foundation stock of sugar beets having adequate curly top resistance, it has been possible to maintain this resistance and select in other directions, incorporating new characters in the variety that has the primary or indispensable attribute—in this case, resistance to curly top.

4. *Black Root Resistance*[4]

a. Resistance to Disease Complex Found. As noted, the humid area has frequently had years of unprofitable sugar beet production because seedling diseases so reduced stands that not enough sugar beet plants remained in the fields to utilize the soil space efficiently or to produce tonnages adequate to pay costs of culture (Coons, 1953b). With such conditions occurring year after year, the beet sugar factories found it difficult to contract adequate acreage for economical factory operation, and the farmer, expecting the beet crop to yield at best only a small margin of profit, tended to slight it with respect to fertilizer and care. Thus, low yields started a vicious circle that led to closing of factories and abandonment of the culture of the crop.

The seedling diseases commonly lumped under the term "black root" have, more than any other factor, been responsible for the low average yields of sugar beets in the more eastern sugar beet districts whenever rainfall has been normal or above. The low yields of sugar beets in the humid area in the past can definitely be attributed to poor, gappy stands. A study made some years ago in Michigan (Lill, 1947) showed for a typical sugar beet district that the average stand of beets over a five-year period ranged, for the various row widths, from 63 to 69 per cent, so low that root yields could not reach half of normal production. Studies by Coons *et al.* (1946) showed that in the seedling disease com-

[4] The breeding of black-root-resistant varieties was conducted by the same group that worked on leaf-spot–resistant varieties, with the names of the late J. E. Kotila, and of C. L. Schneider to be added. The investigations were carried on in cooperation with the Colorado, Michigan, Minnesota, New Mexico, and Oregon Agricultural Experiment Stations and the beet sugar companies comprising the Farmers & Manufacturers Beet Sugar Association.

plex the water mold described by Drechsler (1929), *Aphanomyces cochlioides* Drechs., was most important in causing loss of stands. *Pythium* spp., *Phoma betae* (Oud.) Frank, and *Rhizoctonia solani* Kuehn (*Pellicularia filamentosa* (Pat.) Rogers) bring about an acute disease, but are amenable to control by seed treatment with a fungicide. In contrast, *A. cochlioides* produces a chronic disease whereby the small feeding roots are killed as formed, so that the young beet fails to make effective contact with the soil.

In 1940 and 1941, it was noted by Coons (1947) that certain varieties in the leaf spot resistance tests in Michigan, Ohio, and Minnesota were so badly injured by black root that they could be identified by their reduced stands and by their weak, stunted growth. On the other hand, the inbred, US 216, was outstanding in all tests, showing a marked resistance to black root; hybrids and the synthetic varieties in which US 216 occurred as a component were outstanding in the tests, showing considerable resistance to black root. Other varieties, notably US 215 and SP 1-9-00, a hybrid, were extremely susceptible. These observations were taken as evidence that factors for resistance to black root exist within the sugar beet complex, particularly in US 216. The black root resistance breeding program was conducted in fields in Minnesota and Michigan that had previous histories of sugar beet failures because of black root. Since leaf spot resistance is necessary for any variety to succeed in the humid area, only inbreds, hybrids, and synthetic varieties that are leaf spot resistant have been used as sources from which to select black-root–resistant individuals.

b. Development of US 400 and Other Black-Root–Resistant Varieties. In 1944, mass selections were made by J. O. Culbertson at Waseca in cooperation with the Minnesota Agricultural Experiment Station, the US varieties grown in leaf spot resistance tests being the chief source of roots. Henderson and Bockstahler (1946) and Bockstahler and Reece (1948) continued the mass selections in 1945 and 1946. Bockstahler *et al.* (1950) have indicated for hybridization of resistant and susceptible inbreds that resistance to black root appears to be transmitted to the hybrid as a dominant character. The breeding for black root resistance was extended in 1947 to include cooperative work with the Michigan and Minnesota Agricultural Experiment Stations, conducted by Gaskill *et al.* (1948), breeding stocks being interchanged between stations. It was extended in 1949 to include Beltsville, Maryland. This station has proved to be a key location, because progenies can here be subjected to severe leaf spot and black root exposures (*A. cochlioides*).

Continued mass selections and, more recently, the polycross breeding method developed by Tysdal and Kiesselbach for alfalfa improve-

ment (1944) have yielded several varieties that essentially retain the leaf spot resistance of the parental strains—probably adequate for all ordinary exposures—and which in addition are definitely resistant to black root. That the resistance is probably restricted to *A. cochlioides* is stressed, since in the experimental work all seed is treated to minimize cross effects that might come if the progenies were exposed in one season to one of the seedling diseases and then to another of the diseases the next season.

The first release, US 1177, showed marked superiority over the European check and over US 216 × 226, itself a variety with some

FIG. 7. The sugar beet variety, US 400, resistant to both leaf spot and black root, is shown in the two-row plots at the right and at the left of the susceptible variety in the center. The latter is dwarfed by black root that has killed the lateral feeding roots of the affected plants; the foliage of the susceptible variety is blighted by *Cercospora* leaf spot, whereas the leaves of US 400 are still functioning. (Plant Industry Station, Beltsville, Maryland, September 1, 1954.)

black root resistance. In three tests in 1951 (Coons *et al.*, 1952), in which black root was a factor, US 1177 averaged 777 pounds more sugar per acre than the commercial variety US 216 × 226. In the same set of tests, there were present some reselections from US 1177 and related strains, and these exceeded the parental strains by about 300 pounds of sugar per acre. The beet sugar industry decided not to make extensive commercial seed increase of US 1177 but to await the release of a reselection from it. This now is being introduced as US 400, and it will find its widest use in Michigan, Ohio, Illinois, and Wisconsin, where both black root and leaf spot commonly cause serious losses (Fig. 7).

Comparable work by Doxtator and Downie (1948) with much the same methods has given black-root–resistant varieties for use in Minne-

sota and Iowa. Reports of more recent work have been given by Doxtator and his associates (Doxtator *et al.*, 1950; Doxtator and Finkner, 1954).

5. *Varieties Combining Leaf Spot and Curly Top Resistance*

A further example of the possibilities of combining factors for disease resistance in one variety is afforded in the development of US 104. To meet the needs of certain sections of California, Colorado, western Kansas, and other western states where both curly top and leaf spot are known to cause serious damage, a productive variety with resistance to both diseases would be extremely valuable. As basic breeding material, leaf-spot–resistant inbreds were hybridized with US curly-top–resistant varieties and then backcrossed (Stewart, 1947, 1951). By repeated selection, usually alternated by generations, for leaf spot resistance at the Plant Industry Station, Beltsville, Maryland, and then for curly top resistance at the New Mexico Experiment Station, State College, New Mexico, resistance to both diseases became stabilized in one variety at a level adequate to meet the needs of most areas.

6. *Contributions of the Breeding Program*

The various sugar beet growing districts of the United States now have adapted varieties that largely avert the major threats from disease, except those from the sugar beet nematode and virus yellows. In the previous discussion of the serious disease situations that occur in our sugar beet growing districts, the individualized results obtained by disease-resistant and otherwise improved varieties have been cited. It is interesting to note that the contributions from improved varieties, coupled, to be sure, with the improved agriculture that always comes when a depressing influence is removed, are reflected in the crop statistics of sugar beet production for the nation as a whole. It should be pointed out that the data dealing with our national sugar beet production are actual production figures—not estimates—that are gathered from individual beet sugar factories. They represent actual tonnages of sugar beets delivered from measured acreages. The average yields of sugar beets for the United States for a 50-year period, beginning 1906 and ending in 1953, have been grouped by 5-year periods, thereby smoothing out the small annual variations. It will be seen that the average acre yields of sugar beets show a steady climb since 1934, rising from mean yields that have hovered around 10 to 11 tons per acre or less in the period 1906 to 1935 to reach for the last 5 years an average production of about 15 tons per acre; and this is a sustained production, no year in the last 5 having dropped below 14 tons (Table I).

The yields of sugar follow the same trend as root yields, advancing from below 3000 pounds of sugar per acre for the first three decades to average yields of over 4000 pounds per acre in 1951, 1952, 1953, and 1954. Sucrose percentages show a considerable contrast to the root and sugar yields. The percentages increased gradually until the mid-thirties and since then have shown steady decline to about the 1930 level. It is suspected that in certain areas virus yellows may be one factor influencing the recession in quality.

TABLE I

Average Acre Yields of Sugar Beet Roots, Sucrose Percentages, and Acre Yields of Sugar in the United States by 5-Year Periods, 1906–1950, and the Annual Averages for 1951–1954. Compiled from U. S. Department of Agriculture's *Agricultural Statistics*

	Average acre yield roots, tons	Average sucrose, % (recovered)	Average acre yield sugar, lb.
1906–1910	10.2	12.27	2485
1911–1915	10.4	12.76	2682
1916–1920	9.5	12.56	2356
1921–1925	10.1	13.12	2639
1926–1930	11.0	13.70	2991
1931–1935	10.9	14.98	3251
1936–1940	12.2	14.65	3565
1941–1945	12.4	14.18	3320
1946–1950	14.1	13.81	3896
1951	15.2	13.81	4191
1952	15.3	13.86	4238
1953	16.2	13.99	4505
1954	16.0	13.27	4246

With so many of the primary or what may be called the factors limiting production now being met, and the point having been reached where reasonably good crop production is assured in spite of disease or untoward climatic effects, breeding research may now be directed toward the incorporation of new and desirable characters, toward enhancement of quality, and to better adaptation of varieties to local conditions—all of which should lead to increased productivity. For accomplishment of the broad purposes of the improvement program, genetical research has furnished some intriguing approaches. At many laboratories and field stations, breeding programs are under way to capitalize upon these recent advances. A few of these will be discussed as a sort of prologue for the new era in sugar beet improvement (page 117).

7. Other Serious Disease Problems

In the Midwestern, the intermountain, and the Pacific Coast sugar beet growing districts, the sugar beet nematode is becoming of extreme importance. It causes a wilting of the sugar beets and when the soil is heavily infested crops are worthless.

The sugar beet nematode, a parasitic worm, is one of the worst pests of the sugar beet. Failure to practice proper crop rotation leads to serious infestation.

Practical control depends on starving out the nematodes by rotation of beet crops with crops not attacked by the nematodes. Usually such crops are grown for five years between sugar beet crops. Alfalfa, grains, tomatoes, potatoes, beans, peas, and sweetclover may be used as rotation crops. Cabbages, cauliflower, table beets, mangel-wurzel, turnips, rutabagas, and radishes must be avoided, as they are attacked by the sugar beet nematode and not only permit the nematodes to increase, instead of decrease, but are often injured severely. Special attention should be given to weed control during the rotation period, as the sugar beet nematodes can also live on many common weeds. Thus, in California, mustards in alfalfa fields must be killed. The long period between beet crops is necessary because the female sugar beet nematode develops into a tough cyst which remains in the soil for many years. Enclosed in the cyst are eggs with larvae which can remain alive and capable of attacking plants for many years. In the absence of a host crop, only a small proportion hatch each year and die of starvation and other natural causes, so that it takes several years to reduce their numbers sufficiently so that a good sugar beet crop can be grown.

Success of the five-year period, or more, between beet crops in restoring the land to its former productivity for sugar beets is remarkable. It should not, however, encourage the grower to follow up with a second crop of sugar beets, since the starvation period does not kill all nematodes and sugar beets will have brought back a high nematode population.

The attempts so far to breed nematode-resistant sugar beets have not been successful. Experiments are now under way to explore the possibilities of finding genes for nematode resistance, not alone in the cultivated varieties of beet but among the wild forms of *Beta* as well. Fundamental work on this problem is being done by the Institute for Sugar Production at Bergen op Zoom, Netherlands. In the United States, a cooperative research program is being inaugurated between the Beet Sugar Development Foundation, the California Agricultural Ex-

periment Station, and the Field Crops Research Branch of the Agricultural Research Service of the U. S. Department of Agriculture.

Virus yellows, long known as the most serious disease attacking sugar beets in Europe, was found in 1951 in Michigan, Colorado, Utah, Oregon, and California. It is probably widespread in the United States and may have been here for some time but overlooked. This virus is spread by aphid vectors, of which the green peach aphid, *Myzus persicae* (Sulz.), is most important. Only the older leaves show the disease symptoms. They turn a greenish yellow, particularly at their tips. The veins stay greener than the interveinal tissue. The leaf blades become thick and brittle. If a plant is attacked early, its root growth is checked and storage of sugar is strongly reduced. In the European experience, with early attack, sugar production may be cut from 40 to 50 per cent. If the attack occurs in August, damage may be much less.

Totally infected fields were found in California in 1951 and 1952. Instead of a normal green color, the fields were canary yellow. The condition had been known for several years in California as "Salinas yellows" but now is identified as virus yellows. Because infection was total, there was no measuring stick of healthy fields for determining effects of the disease. In 1952 the disease was prevalent in Colorado, where it appeared in late August. Early records indicate that the disease probably occurred in Colorado as far back as 1940.

Studies in California have shown that the disease may strikingly reduce root weight and cause strong declines in sucrose percentage. In light of present knowledge, virus yellows may rank with curly top as a serious menace.

Control measures now in use in Europe are not likely to be of particular applicability in the United States. There is some evidence that breeding for resistance to virus yellows may be fruitful, but no resistant varieties have as yet been developed.

V. Sugar Beet Improvement Entering New Era

1. Basic Information Available to Breeders

The increased production that has been achieved, which is parallel to that with corn attributable to corn breeding research, has been the work of the federal and company breeding programs that have been implemented by beet sugar companies in bringing seed of the improved beet stocks promptly and in adequate quantities to their growers. The federal work has been conducted in cooperation with state agricultural experiment stations and technologists of beet sugar companies. The

companies are continuing their cooperation and financial support of the federal research. In addition to the federal breeding investigations, the major beet sugar companies of western United States have extensive research programs aimed at breeding varieties adapted to their respective areas, and these varieties have had important effect on the general improvement in sugar beet production of the respective districts concerned. Interchange of ideas among sugar beet breeders is fostered by a Breeders' Forum sponsored by the Beet Sugar Development Foundation. This forum has centered its attention upon an appraisal study of inbreds, participants contributing such breeding material as available for replicated trials whereby a catalogue of important characteristics of available inbred stocks could be compiled.

The research on sugar beet agronomy conducted in Europe, as summarized by Roemer (1927), and that on genetics and breeding, as reported by Munerati (1929), Vilmorin (1923), and Schneider (1939), constitute the starting points for many of the advances made in sugar beet investigations in the United States. The investigations on the morphology of the vegetative and reproductive organs of the sugar beet by Artschwager (1926, 1927) are built upon the earlier European studies, especially those of De Vries (1879) and others. The European research on wind and insect transport of pollen has been summarized by Archimowitsch (1949). Investigations by Stewart (1946) in the United States have centered on wind pollination as of greater significance. The presence of viable pollen in the upper air currents has been demonstrated by Meier and Artschwager (1938), and this is a factor in obtaining strict isolations. In the sugar beet seed field, however, the dispersal of wind-borne pollen, as shown by Stewart and Campbell (1952), is highly localized and shows a curvilinear relationship, the amount of pollination from a given pollen source being inversely proportional to the distance in feet. The study of methods of obtaining pollen-free isolations as initiated by Nilsson (1922, 1923) at Svalöf, Sweden, was extended by Brewbaker (1934); as a result of these studies, investigations in the United States have chiefly employed bagging techniques with sugar beets coming into flower, in which individual branches are enclosed in parchment or Kraft paper bags. Only limited use has been made of the cage-type of isolations suggested by Munerati (1920) or the cloth bag types of Vilmorin (1923).

2. *Polycross Method Applicable in Breeding Sugar Beets*

Breeding and genetics research with sugar beets has drawn heavily on the advances made with other crop plants, both for theory and methodology. Thus, as previously noted, the polycross method as de-

vised for alfalfa improvement by Tysdal and Kiesselbach (1944) is being applied in the breeding of sugar beets for black root resistance. Brewbaker and Wood (1948) reported results with sugar beets obtained essentially by this method.

The first step in the polycross method conforms to the principle originally set forth by Vilmorin, that the best criterion of the breeding value of a selected plant is the performance of its progeny. Open-pollinated seed, produced from selected plants which are brought to flower in an isolated plot where random pollination is expected to occur, are used in field tests to evaluate the breeding value of the mothers. The genotype of the mothers is propagated through selfed seed or by clones which can be established without difficulty from stalk cuttings, as indicated by Owen (1941). The outstanding mothers, as indicated by the field performances of the open-pollinated progeny, are intercrossed to produce a synthetic variety, or possibly a strain for a second cycle of selection. Repeating the breeding cycle would be essentially recurrent selection, which has been found, for other crops, an effective method of improvement.

3. *Application of Other Breeding Methods*

Tester strains to evaluate inbreds have been investigated by Deming (1942), who suggested utilization of the red garden beet as the topcross parent, because of the ease of recognition of the hybrid. This method has been given further study by Oldemeyer (1954). Marker characters, especially the simple Mendelian character *R* which governs red hypocotyl and red bud color in sugar beets, have been utilized for identification of the hybrid between *RR*, *Rr*, and *rr* genotypes. The inheritance of hypocotyl color was first worked out by Linhard and Iverson (1919) and confirmed by Keller (1936). Nuckols (1931) showed that hypocotyl color did not influence yield of roots.

In Europe and the United States, the correlation of morphological characters with yield and quality has been studied. Pritchard (1916a) and Pack (1930) have reviewed European literature and reported their own findings. The correlation of leaf, stem, and root characters, or of readily noted growth habit with sucrose percentage, has not been fruitful in revealing indices for high sucrose. Artschwager (1930, 1952) has suggested a positive correlation of high ring density and core type of the root with high sucrose.

As discussed earlier, European breeding methods for sugar beets, particularly those of the seed-breeding establishments, were less influenced by Johannsen's pure-line concept than those of the United States; hence, in any comparison of breeding materials available for

analyses of the role of genetic factors, this difference in approach should be borne in mind. Apparent contradictions between European and American results frequently can be explained by the consideration that, with the former, conclusions often were drawn from a population rather than from a single biotype. The European research on sugar beet improvement and the related studies on cytogenetics constitute a body of knowledge that should not be neglected. This review, although centering on American contributions, has made some attempt to tie in these with the pertinent European contributions.

4. *Heterosis*

It was generally postulated as, for example, by Vilmorin (1923), following the discovery of heterosis in *Zea mays*, that sugar beet hybrids would show a similar type of response. Only observational evidence was adduced in this regard prior to the experiments at Fort Collins in 1932 by Stewart *et al.* (1940).

In the Fort Collins study, 41 F_1 hybrids, obtained by mating inbred sugar beets in isolated seed plots, were used. To produce the hybrid, the two strains to be crossed were brought to seed production in a location at considerable distance from any other sugar beets. In the progenies grown from the various hybrid seed lots (usually reciprocals were taken), there occurred not only F_1 plants but selfs of the inbred strain that was the seed bearer. Where possible, the data on performance of a progeny were based upon the F_1 class of plants, but in many cases the entire population, regardless of extent of hybridization, was taken. The comparisons were made in 8$\times$ or 6$\times$ replicated tests, the quantity of seed dictating the type of test that could be conducted. In 31 of the 41 cases tested, the root weight of the hybrid was significantly greater than the root weight of the parent strains appropriate for the comparison. The average gain in root weight of the hybrid over the parental mean was 42.5 per cent, but it was recognized that this percentage is greatly influenced by the relative yielding abilities of the inbreds entering a given cross. The average sucrose percentage of the hybrids did not differ significantly from the average of the inbred parents. In the tests, effects attributable to the resistance to leaf spot of certain inbreds and hybrids could not be separated from effects associated with hybridity. The conclusion was drawn that direct appraisal of the effects of hybrid vigor in increasing root weight could not be made, but the gains in root weight of certain hybrids over the commercial brand used as a check were enough beyond those reasonably attributable to superior disease resistance to indicate definite increase in productivity from heterosis.

A further study of heterosis in sugar beet single crosses was con-

ducted at Ault, Colorado, in 1942 and 1943 by Stewart *et al.* (1946), using 35 sugar beet hybrids obtained by mating (1) 11 inbred strains and (2) an open-pollinated variety (US 22) with each of 3 pollen parents, inbred US 215, inbred US 216, and EUROPEAN CHECK. In two tests (one 7$\times$ replication, the other 8$\times$), root yields, sucrose percentages, and sugar production were studied in hybrids and parents. Leaf spot was not a factor in these tests, and the data were drawn exclusively from identified F_1 plants. All the inbred strains were relatively high yielding. Futhermore, the variety known as EUROPEAN CHECK is very productive under conditions where leaf spot is not a factor. With such initial breeding material, relatively few hybrids would be expected significantly to exceed, in the attributes measured, the means of parents or

FIG. 8. Hybrid vigor in sugar beets. Representative roots of the hybrid US 215 X 216 are shown at the center. Piled at the right and left are similar numbers of roots of US 215 and US 216, respectively, the parents. (Arlington Farm, Virginia, October 25, 1939.)

EUROPEAN CHECK. It was found that, as a class, the hybrids were significantly superior to the parents. Definite heterosis effects were shown to occur in sugar beets, but in comparison with the higher yielding inbreds and with a high-yielding commercial variety, relatively few hybrids gave significantly high performances. Six of the hybrids were significantly above EUROPEAN CHECK in production of sugar. There was evidence from the experiments that, with many inbreds to evaluate, EUROPEAN CHECK might prove effective as a tester. Doxtator and Skuderna (1946) and Kohls (1950) have shown in their reports a similar tendency for heterosis to occur in sugar beet hybridizations.

An illustration of the type of response obtainable from appropriate matings is given in Fig. 8; the hybrid, US 215 $\times$ 216, is shown at the center with the parental inbred varieties US 215 and US 216 at right and left respectively.

With the curly-top–resistant varieties, there is clear-cut evidence that hybrid varieties, properly chosen for adaptation to the particular districts concerned, hold the key to increased productivity. In particular, the data from Utah, Idaho, and Washington experiments on the performance of hybrids are very impressive. For example, at Twin Falls, Idaho, in 1952, US 22/3 produced 31 tons of sugar beet per acre, whereas the hybrid produced 35 tons with an improved sugar content. In a series of tests conducted in Utah and Idaho over a four-year period, the yields of the better hybrids have shown consistent gains over US 22/3, ranging from 10 to 20 per cent in acre yields of sugar.

It must be recognized, however, that the hybrid variety as made between two inbred strains does not have the range of adaptability shown by an open-pollinated variety, and more years of tests are required to fit the various hybrids into the districts for which they are best suited. A hybrid that was highly productive in a number of tests suffered badly from blister beetle attack when planted in Washington. This illustrates what may happen when the genetic base is narrowed in the hybrids from what is presented in the open-pollinated variety. It seems safe to forecast that research on hybrids shortly will have progressed far enough so that dependable, high-yielding hybrids can be released for the curly top area.

5. *Male-Sterility in Sugar Beets*

Male-sterility produced by combining cytoplasmic and genic inheritance was found by Owen (1945) in cross-pollinated varieties of sugar beets bred for resistance to curly top, notably in US 1, US 33, and other selections from this basic breeding stock. Complete male-sterility was characterized by the occurrence in the flowers of white, empty anthers (Fig. 9). Semi-male-sterility also was found. Assuming two types of cytoplasm, S for male-sterility and N for normal, and two Mendelian factors, X and Z, the majority of the evidence, including striking differences from reciprocal crosses, indicates a genic constitution of male-sterile and semi-male-sterile beets, as follows: $Sxxzz$ types are completely male-sterile; $SXxzz$ or $SxxZz$ are semi-male-sterile, usually without viable pollen; and $SXxZz$ are semi-male-sterile, usually with some viable pollen, and sometimes indistinguishable from the normal hermaphrodite.

The male-sterile factor in beets, therefore, conforms with the pattern described by Gairdner (1929) for flax, and that for onions by Jones and Clarke (1943), but in both of these plants only one Mendelian factor is involved. Cytoplasmically inherited male-sterility offers many advantages to the sugar beet breeder. However, to be most useful, it

must be easily obtained in progenies in which 100 per cent of the plants are completely male-sterile. Progenies approaching this condition are not only possible but are common among controlled crosses to the male-sterile beets. Some crosses to male-sterile beets do not produce uniformly

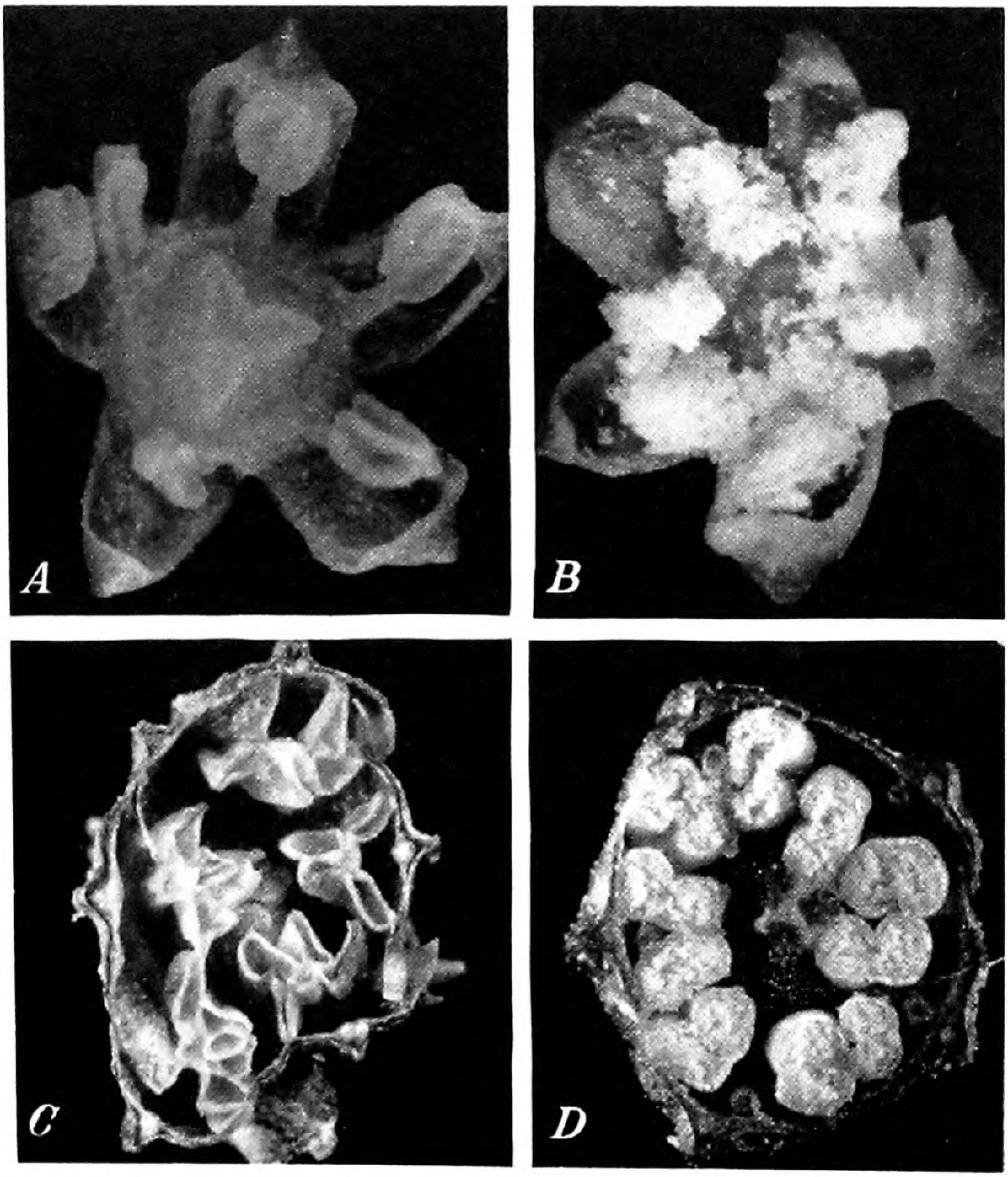


FIG. 9. Sugar beet flowers. *A*, Male-sterile; ×12. *B*, Normal, immediately after dehiscing of anthers; ×12. *C*, Cross section of male-sterile flowers in bud stage; ×21. *D*, Cross section of normal flower in bud stage; ×21.

male-sterile offspring, and genic effects have been recognized which appear to modify the expression of cytoplasmic inheritance.

Owen (1948) has designated three general types of pollen parents as O, I, and II. These pollen parents carry N type of cytoplasm and can be used either as females or pollen parents. They cannot be dis-

tinguished by their appearance, but they represent different genotypes and therefore differ in breeding behavior. If crossed to a cytoplasmically male-sterile plant (*Sxxzz*), type O (*Nxxzz*) gives an offspring that is all male-sterile; type I gives mostly male-sterile offspring, but 5 to 30 per cent may be semi-male-sterile; and type II gives a progeny that is 50 per cent male-sterile, 25 per cent semi-male-sterile, and 25 per cent more or less normal with respect to pollen production. Obviously, for effective use of the male-sterile factor, types I and II, which are heterozygous genotypes, are undesirable. Owen (1950) has pointed out the need of proved stocks of *Sxxzz* genotype as male-sterile parents in matings to establish the three types. Some plants which may be considered as *SxxzZ* in constitution may appear completely male-sterile owing to environmental influences.

By a series of backcrosses, the male-sterile factor can be incorporated in a variety, once O types are found. After two or three backcrossings, using the O type as the recurrent parent, of course, the male-sterile plants resemble the pollinator, and for practical purposes the third or fourth backcross generations may be considered its pollen-sterile equivalent. The practical utilization of the male-sterile equivalent requires that an O type pollinator be isolated and preserved. With it a constant and 100 per cent male-sterile progeny can be produced essentially representative of its perfect flowered prototype.

The male-sterility factor puts in the hands of the plant breeder a very powerful tool. As mentioned previously, the production of hybrids between inbred lines is relatively inefficient if intercrossing must be left to chance. By virtue of their very nature and the means employed in their purification, inbreds, after many years of inbreeding, tend to become self-fertile and as hermaphrodites are ineffective in hybrid seed production. Now that cytoplasmic male-sterility is available, self-fertility of an inbred strain is an asset in preserving the O type after it has been located and is no handicap when used as a pollinator.

In addition to cytoplasmic male-sterility, Mendelian sterility has been found in sugar beets. Owen (1945) had noted this type and in more recent work (1952) has isolated plants carrying either genes a_1 or a_2, the symbols chosen to designate abortion of pollen. He has proposed the following utilization of both types of male-sterility in the production of improved varieties to give a four-way hybrid $(A \times B) \times (C \times D)$ carrying desirable characters. This may be cited as illustrative of the use of male-sterility in sugar beet improvement.

As proposed for production of a curly-top–resistant variety, strain A can be a male-sterile phase (*Sxxzz*) of a variety carrying curly top resistance, and it is mated with an appropriate O strain (*Nxxzz*) B as

pollinator to give a completely male-sterile hybrid progeny. The C grandparent may be a Mendelian male-sterile (*aa*) from curly top strains having high sucrose percentage, such as US 35, and rogued to give only pollen-sterile plants. The D grandparent would be the pollinator (*AA*) to give the hybrid C $\times$ D. Sample crosses of the respective types are now under production, the first-named single cross (A $\times$ B) being male-sterile and the latter *Aa*, a heavy pollen producer that is extremely vigorous and known to transmit desirable attributes to the offspring.

Thus, the production of double hybrid sugar beets is feasible and will not add greatly to the cost of growing seed over present methods. The pollinator indicated as C $\times$ D may be discarded before harvesting the commercial seed, since it is required in small proportions, but satisfactory yields can be obtained from the seed bearer A $\times$ B. Male-sterility conditioned by Mendelian genes in grandparent C can be produced to the extent of 50 per cent of the population by appropriate crosses. Therefore, the job of roguing to produce the pollinator C $\times$ D is not a serious problem.

Other combinations are also under test. If monogerm research is successful, the female parent A $\times$ B in the double cross may be taken from monogerm types. The successful production of male-sterile monogerm types has been reported by Owen *et al.* (1945). The pollinator C $\times$ D need not be monogerm, for commercial seed is taken from the monogerm male-sterile parent, A $\times$ B.

In addition to using a gene for pollen abortion, Owen suggests utilizing gene *B* for annual habit (Owen, 1952; Owen *et al.*, 1954). With the gene *B* present, thermal induction is no longer necessary and three or four generations can be grown in a single year under warm temperatures and continuous illumination. After the desired degree of homozygosity has been reached in successive backcrosses and the desired gene or genes have been transferred from the nonrecurrent to the recurrent parent, genes *B* for bolting and *a* for abortion of pollen may be eliminated by selfing. No injury should result to the final inbred by carrying gene *B* for bolting up to the last backcross operation. So long as the annual habit is produced by a single gene and segregation is clear-cut, this should not influence the bolting tendency of the final inbred.

6. Monogerm Sugar Beets

The seed ball of the beet is a glomerule containing one, two, three, to many true seeds. A sugar beet plant that would bear single-germed fruit has long been sought and, fully 50 years ago, experimental work to this end was started. It had no success, but the advantages of mono-

germ seed as stated then as a means of saving hand labor in our beet fields are just as cogent today as when first proposed by Palmer (1918). During World War II, as a labor-saving device, Bainer (1942) devised a method of shearing multigerm seed balls to produce planting stock that was prevailingly single-germ. This was widely adopted, and Bainer's improved method (Bainer and Leach, 1946) of decorticating seed, plus the breaking up of large seed balls, is now used to provide planting stock for a high percentage of United States acreage. Processed seed as now used is obtained by rubbing off the corky ridges of the seed balls, by breaking the large seed balls, and by screening, so that the planting stock ranges between $^{6}/_{64}$ and $^{10}/_{64}$ inch in diameter, broken pieces and small seeds being sifted out and discarded and larger ones screened off for further size reduction. A seed piece usually contains from one to two germs to, occasionally, three germs. As a result, carefully sized seed can be used in precision drills set to drop a single seed piece at about 1-inch intervals in the drill row.

Processed seed and the mechanized operations that are made possible by it have made definite contributions as valuable labor-saving methods. The importance of these to industry has been summarized by Smith (1950). The sparse stand that is obtained with processed seed can be thinned by down-the-row stand-reducing machines that take out at random, by means of rotating cutting knives, a predetermined portion of the row, the grower being able to go over the row a second or even a third time to accomplish a greater degree of stand reduction, if such is desired.

It is generally conceded, however, that the processing of seed is wasteful and expensive. Many farmers enthusiastic for processed seed still have laborers perform by hand the customary operations to give the desired stand of single plants uniformly spaced and thoroughly weeded. Others furnish their laborers with long-handled hoes to go over the fields for trimming out surplus plants and to give additional weed control.

For these reasons, the industry had great interest in the discovery of monogerm seed by V. F. Savitsky and his colleague, Bordonos (1941), in the U.S.S.R., and took steps, when the former was driven out of that country, to make it possible for him to continue his genetical research in the United States. Knowing what to look for, Savitsky found in Oregon in a variety designated as MICHIGAN HYBRID 18, a few plants the seed balls of which were truly monogerm. From these, Savitsky (1950) obtained his monogerm race SLC 101 and a companion variety SLC 107, both considered true monogerm plants. Savitsky (1952a, b) has shown that, in SLC 101, monogermness is controlled by a single re-

cessive Mendelian factor. Hybrids have been made by Owen, *et al.* (1954) between the monogerm types (*mm*) and multigerm varieties (*MM*) having high curly top resistance. Stewart (1952) has made hybrids with multigerm leaf-spot–resistant varieties. The monogerm varieties found by Savitsky tended to be of a slow-bolting type—a desirable character in itself, but one which has complicated the production of hybrids with monogerm stocks.

Incorporation of the monogerm character has been accomplished either by selection of the segregates in the F_2 and F_3 generations following the first cross or by backcrosses followed by reselection for monogerm types (Savitsky, 1952b).

It is too early to predict when monogerm lines will be available for commercial use. It is obvious that, with a commercial variety at a given stage of development, several years are required to make that variety monogerm. In the meantime, further improvement of the multigerm variety may make it desirable to start afresh. Once varieties are stabilized for major characters, the job of making them monogerm can be efficiently done.

Owen has suggested a method that has been used in seed production, by which male-sterile monogerm types of reasonable productivity and with some curly top or leaf spot resistance, as the case may be, can be immediately utilized. The male-sterile monogerm type is used as the seed bearer and the pollinator can be any multigerm type chosen because of qualities it may contribute to the hybrid. The F_1 seed produced on the male-sterile monogerm seed bearer will, of course, be monogerm. New stocks of seed must be made each year by the same procedures, since any direct increase of the hybrid would give a multigerm product.

7. *Bolting*

In the more northern latitudes of Europe and America, bolting in early-sown sugar beets has been of great concern for many years. Munerati (1942) gave a review of the literature of more than 250 references to bolting, as well as the results of his own researches. He established strains resembling the sugar beet that passed from the vegetative to the reproductive phase of growth in only a few weeks after germination, and with continuous light exposure, as many as five generations could be obtained in a single year. Annualism, as established in this strain, was transmitted as a dominant character in crosses with sugar beets of the normal biennial cycle of growth. Abegg (1936), using an annual strain supplied by Munerati, has shown that the annual tendency is conditioned by a single dominant gene, *B*.

If given a favorable environment for growth, the vegetative and

reproductive phases of the annual beet can be controlled readily by length of the photoperiod (Munerati, 1929). The annual beet and the sugar beet are long-day plants, but for the sugar beet a period of thermal induction at temperatures below 20° C. is a basic requirement for flowering, as has been demonstrated by Chroboczek (1934). According to Stout (1946), temperatures of storage for beet roots above 10° C. tend to reverse the induction process. Thus, roots of a nonbolting type of sugar beet stored for 43 days at 9.1° C. bolted 98 per cent, whereas storage at 10.6° C. resulted in only 79.5 per cent bolting after 43 days, and storage at 13.2° C. showed, after 43 days, only 23 per cent bolting. The thermal induction period required for abundant seed production may be reduced by long photoperiods, as shown by Bell and Bauer (1942, 1943) and Bell (1946). They also proposed that a combination of photoperiod and thermal induction may be used as an effective means of selection for nonbolting types of sugar beets. Stout and Owen (1942) tested vernalization techniques with sugar beet seeds and found it a practical measure for hastening reproduction under controlled greenhouse conditions, but probably impractical in the field because warm conditions in the seed field might reverse the process. Gaskill (1952a) demonstrated that a combination of continuous light and low temperature exposure to seedlings can be used to bring about two generations a year of biennial sugar beets. The principle that cool temperature and photoperiod are complementary influences in hastening sexual maturity in the sugar beet has received wide applications by sugar beet breeders in the United States as a means of reducing the time required in reaching an objective in breeding programs.

The mode of inheritance of nonbolting in the sugar beet has had several interpretations. No doubt some of the difficulty in reaching a satisfactory explanation has been the failure to recognize the complementary effect of photoperiod and low temperature, which has been designated by Owen *et al.* (1940) as photothermal induction. These investigations have shown that there is genetic variability with regards to temperature and photoperiod response in both annual and biennial beets. They recognized a genetic factor for bolting, designated B', which is allelic to the factor B for the annual tendency described by Abegg (1936). Genetic factors B and B' are dominant to b associated with the nonbolting tendency. Linkage, as shown by Abegg (1936) and by Owen and Ryser (1942), between B' and the color factor R made the genetic interpretation possible.

8. *Polyploidy*

Tetraploid cells in roots of the sugar beets were reported from Europe as occurring naturally, but current production of completely

polyploid sugar beets has come from the use of colchicine. As with other species, tetraploidy in sugar beets manifests itself by cell enlargement, thereby permitting prompt recognition of increased ploidy by stomatal size, size of pollen grains, etc. In experimental work with sugar beets, it was soon found that the greatest difficulty in the production of true tetraploids was the confusion of chimeras with the plants whose tissues were 100 per cent tetraploid. The generation following colchicine treatment is further complicated by the occurrence of aneuploids, making actual chromosome counts the only safe criterion in the establishment of autotetraploid strains of sugar beets. The experience in the United States with colchicine-treated sugar beets is parallel to what is reported from Europe.

The first polyploid beets produced in federal laboratories were obtained by Abegg (1940b) in 1939 and reported in 1940. At the same time, Artschwager (1940) made a similar report and in 1942 detailed his method (1942). Peto and Boyes (1940) and Peto and Hill (1942), in Canada, produced tetraploid and triploid beets and rapidly pushed these to the point where agronomic tests could be made. They found distinct advantage from the polyploid types. In Europe, under the direction of V. Lund, J. Rasmussen, and L. A. Schloesser, tetraploid and triploid sugar beets have been produced, the varieties arising from their respective laboratories being known as MARIBO P., HILLESHÖG K POLY., and KLEINWANZLEBEN POLYBETA. For the most part, polyploidy is utilized by means of a population obtained by intercrossing a tetraploid with a diploid, the population showing both of these types in considerable percentages but, presumptively, the highest percentage is triploid. Lüdecke has conducted evaluation tests with them, interpreting the results optimistically (1954).

Dr. Helen Savitsky (1952b) has made a notable contribution by way of a precise colchicine treatment of seedling beets, which produces a maximum of tetraploid plants. By this treatment she has produced tetraploid equivalents of US 22/3 and related curly-top–resistant stocks. By use of male-sterility, triploid hybrids have been made with this new material which, in preliminary field tests, look very promising.

The experience in the United States has not as yet shown positive advantages from tetraploids or triploids. The first tests were conducted by Abegg at Arlington Farm in 1941. In this work, Abegg (1942) dealt with true tetraploids obtained from US 22, US 23, US 215, US 216, the hybrid US 215 × 216, and from an inbred known to have six generations of inbreeding. In a field test in which the performances of the $4n$ types were compared with those of the $2n$ types, no significant differences in productiveness as measured by sugar per acre were found among the types contrasted. In general, the tetraploids had larger leaves

and larger roots but were slower in maturity, so that, when harvested, what was gained in root size was lost by the lower sucrose percentages.

In 1942, some of the Abegg material was planted in replicated tests at Beltsville, Maryland, and Ault, Colorado. The tests were reported by Abegg *et al.* (1946). Here again, no advantage was shown for the 4 *n* types when compared with the 2 *n* types from which they had been respectively derived. Although the roots of the tetraploids sometimes were slightly larger, the differences were not significant. In several instances, both at Beltsville and at Ault, the sucrose percentages were significantly lower for the tetraploid than for the corresponding diploid. As a result, the calculated acre yields of gross sugar were frequently significantly below those of the comparable diploid. In another test, where attempts had been made to induce bolting in 4 *n* and the corresponding 2 *n* types, it appeared that polyploids had a lessened tendency toward bolting, as also reported by Levan (1942) and by Levan and Olsson (1944). A study of the seed balls, as reported by Abegg *et al.* (1946), indicated a lessened number of viable seeds per seed ball in the 4 *n* types as compared with the 2 *n*. The average number of seed balls containing a single viable seed for tetraploids derived from US 22 or US 23 was 72 per cent, compared with 34 per cent for diploid US 22. The seed ball size classes were kept the same in these comparisons. Similarly, tetraploids US 215, US 216, and US 215 × 226 showed, respectively, 63, 74, and 58 per cent seed balls with single viable seed as compared with 24 per cent for diploid US 215 × 216. These seed balls have naturally about the same condition of single germness as is obtained by carefully processing diploid seed. No utilization commercially, however, has been made of this tendency.

In this work, no advantage in productivity could be attributed to autotetraploidy. The 4 *n* types tended to remain vegetative and were delayed in maturity. They were noted by Gaskill to be frost-sensitive in Colorado as compared with the 2 *n* types. This would operate against extending the growing period for these slow-maturing types in most sugar beet districts, but in California their culture could be maintained as long as desired.

A further test with triploid sugar beets was conducted in 1951 by Stewart and Gaskill (1952). The 4 *n* types established by Abegg were hybridized with unrelated diploid lines. For each of the matings the plants were chosen so that it was possible to identify the triploids by the color of the hypocotyl of the seedlings or by the bud color in the larger plants. Insofar as possible, stands of 3 *n* plants were left at thinning time. Ploidy was disregarded at harvest, except that the percentage of triploid plants in each plot was recorded. The results of the field tests

with three triploid hybrids indicated equivalent productivity in acre yield of roots and gross sugar to that of hybrids that were produced from matings of related lines on the diploid level. The sucrose percentage of the triploid hybrids in contrast to the generally low sucrose percentage of tetraploids showed that the triploids compared favorably with the diploids, but the evidence did not show the great advantage obtained elsewhere.

Sound agronomic evidence published from Europe on the performance of the polyploids is relatively scanty. It can be said that polyploidy per se is not an automatic method of increasing sugar beet productiveness, but this does not mean that tetraploids may not be found that will give superior performance either directly or when used in production of hybrids or a synthetic variety. Similarly, it is not precluded that superior triploids may not arise from the utilization of proper components.

VI. New Sources of Genes

1. *Cultivated Beets, Beta vulgaris* L.

As we have seen, the sugar beet traces to the White Silesian beet selected by Achard from the mangel-wurzel complex grown by farmers around Magdeburg. We have no way of knowing what germ plasm has been lost along the way but, obviously, all steps in breeding have tended toward greater and greater refinement of the population and toward the dropping out of genes.

There are important genic reservoirs that remain to be tapped for sugar beet improvement. Savitsky (1936, 1938, 1940), in his investigations of sugar beet and mangold (chard) hybrids while in the U.S.S.R., found that primitive forms of the mangold presented great interest for genetical and selective experiments with the sugar beet. The high sugar content of F_1 and F_2 hybrids from crosses of sugar beets with mangolds indicated the possibility of segregating forms higher in sucrose than the sugar beet parent. Here is a fruitful field for research, and work along this line has been started in the United States by Savitsky and his associate (Ryser and Savitsky, 1952).

The possibility of establishing in the sugar beet the high root yields found in the forage beet has been intriguing. The investigations of Savitsky (1938) and Bougy (1933) and others have indicated the possibility of obtaining high sugar lines from hybridization of sugar beets and forage beets. The inheritance of factors influencing sucrose percentage in the sugar beet has been studied by Culbertson (1942). Deming (1948) has sought by hybridization to transfer to the sugar beet

the high-yielding capacity and globose root shape of the garden beet. He has succeeded in doing this, but sucrose percentages in the segregates from the initial hybridizations are significantly below those of the sugar beet. By backcrossing and selecting to retain the globose root shape—a character that would facilitate mechanical harvesting—the sucrose percentage may be enhanced. The rapid increase in machine harvesting, which is now a practice on approximately 90 per cent of the total acreage of sugar beets in this country, has emphasized the economic importance of a root shape that will make easier the pulling of the root from the ground.

2. *Wild Species of Beta*

a. Beta maritima L. The wild relatives of the sugar beet represent a great and essentially untouched gene bank. Mention has been made of Munerati's (1932) obtaining factors for leaf spot resistance by crossing sugar beets with the biotypes of *Beta maritima* that occur along the mouth of the Po River in Italy. There is no question that factors for *Cercospora* leaf spot resistance were obtained, but the breeding job involved was both long and tedious.

Certain collections of *B. maritima* made in 1925, usually from a single plant or a plant colony, when tested by artificial inoculations in the greenhouse and in field tests in Colorado, showed high resistance to *Cercospora* leaf spot. Certain of these collections, when tested by Coons *et al.* (1932) in New Mexico, were highly resistant to curly top. In a few cases, a collection showed resistance to both diseases. Hybridizations with sugar beets were made and the segregating generations were selected for both leaf spot resistance and curly top resistance. The outlook of obtaining resistant strains in this way was promising but not more so than from the selections made from the sugar beet itself. Since breeding work with the sugar beet did not present the problems of ridding the progenies of multicrowns and rootiness, the emphasis on wild hybrids gradually dwindled.

In 1951, Stewart revived the investigations with *B. maritima*, first carefully screening a wide selection of types to find individuals with high leaf spot resistance. Already, plants whose natural leaf spot resistance is as great as that of the most resistant inbred types have been found. If the genes in the *B. maritima* plants prove complementary, the way is open for increase of leaf spot resistance beyond what has as yet been found in sugar beets.

b. Other Species of Beta. The other wild species of sugar beet may afford a germ plasm resource that conceivably may decisively affect sugar beet breeding. Within the genus *Beta*, the various authors recog-

nize from 12 to 14 species. Coons (1954) has listed *Beta vulgaris* L., *maritima* L., *B. patula* Ait., *B. macrocarpa* Guss., and *B. atriplicifolia* Rouy as belonging to the Vulgares group. All of these intercross readily and they are undoubtedly closely related. A second group, designated as Patellares, comprises three species, *B. patellaris* Moq., *B. procumbens* Chr. Sm., and *B. webbiana* Moq. These have vinelike growth habit, are perennial, have monogerm, nutlike seed balls, and do not develop a fleshy storage root. A third group is the Corollinae, consisting of *B. trigyna* Wald. et Kitt., *B. lomatogona* Fisch. et Mey., *B. macrorhiza* Stev., and *B. foliosa* Hausskn. These plants occur chiefly in Asia Minor, but *B. trigyna* has been found in Hungary and in the Crimean Peninsula. They are all perennials and are characterized by flowers in which the perianth is more or less corolloid. They have enlarged, woody storage roots which permit these species to withstand extreme drought. A fourth group, Nanae, contains only the dwarf, alpine species *B. nana* Boiss. et Held. Certain of these species are of interest because they exhibit characters sought at present for sugar beet improvement. *Beta lomatogona* and *B. nana* and all the species of the Patellares group are monogerm types. *B. macrorhiza* is characterized by having a very large seed ball. *B. foliosa* apparently has capacity for withstanding both cold and drought.

The $2n$ chromosome number of the sugar beet is 18, and this number holds for nearly all other species of *Beta*. Notable exceptions exist in *B. trigyna* and *B. patellaris*, which have 36 as the $2n$ chromosome number. It is reported that *B. lomatogona* exists as both an 18- and a 36-chromosome form. The hexaploid form of *B. trigyna* is known also from Europe.

Chief attention is now focused on *B. patellaris*, *B. procumbens*, and *B. webbiana* because these species are apparently immune to *Cercospora beticola* and were once thought by Coons (1953a) to be immune to curly top, since inoculations in greenhouse and field exposures in New Mexico failed to bring about obvious signs of curly top. However, Murphy and Giddings (1954) found that *B. patellaris* became infected with curly top during extreme exposures in Idaho in 1953. The three varieties are reported as being unfavorable food plants for the sugar beet nematode; at least cysts are not found on the roots, according to Hijner (1952).

The desirability of hybridizing sugar beets with these species has long been recognized, but the hybrids which are rather easily obtained have not been viable, usually dying when the young plants are only a week or two old. Stewart (1950) was able to bring a sugar beet $\times$ *B. procumbens* to flower and the F_1 plant set seed when pollinated with

pollen from the sugar beet. Unfortunately, the plants of the backcross were as unthrifty as the F_1 generation.

Recently, Gaskill (1954) obtained viable hybrids by crossing chard and *B. procumbens.* The plants have come to flower. Whether the backcross to beet is viable has not as yet been determined. He has been able to obtain evidence that, with respect to infestation with the sugar beet nematode, the hybrid partakes of the character of *B. procumbens.*

Previously, the failure to obtain viable hybrids from matings of the sugar beet and species in the section Patellares has been due to the necrosis of the roots of the F_1 seedlings, the top growth apparently being normal. Coe (1954) has developed a grafting technique, whereby the sugar beet serves as a foster root for the unthrifty F_1 seedling. This grafting technique has made it possible to grow many F_1 plants to the flowering stage, but the sterility of these species hybrids has impeded progress in the development of sugar beet types carrying the genes for disease resistance and for nematode immunity found in *B. procumbens, B. patellaris,* and *B. webbiana.*

VII. The Future of Sugar Beet Breeding Research

Inbreeding of beets has not been a common practice in European laboratories and, aside from the work of Tracy and the years of effort by Deming, few breeders in the United States have made a sustained effort with sugar beets at all comparable to what has been done with other cross-pollinated plants, notably *Zea mays.* Clearly, many recessive factors are not revealed in a crop largely increased by mass selection methods. There is now increased interest in further exploration of the genic resources of the sugar beet itself by the production of great numbers of inbreds. A major project of the Breeders' Forum is the production and test of such inbred material as a gene resource.

All of these efforts can only result in a greatly augmented array of breeding material, the building stones to fashion new and better plants in the future. We may therefore forecast very great steps in sugar beet improvement. The obstacle to the easy production of abundant hybrids, presented by plants whose flowers are perfect, is minimized by the discoveries of cytoplasmic male-sterility and Mendelian male-sterility. The surface has just been scratched in utilizing these powerful tools both in a practical way and in genetic research. There are also great possibilities in utilizing self-fertility and self-sterility—approaches that have been opened by the researches of Owen (1942) and Helen Savitsky (1952a), but which as yet have scarcely been explored. Abegg (1940a) gave a list of characters in sugar beet that had been investigated. To these he assigned symbols. The usefulness of simple Men-

delian factors such as monogermness is being demonstrated, and one can only speculate on possibilities when genetics research throws light on other characters in the sugar beet and demonstrates their inheritance. Polyploidy has at present hardly been utilized with sugar beets as a genetic tool, but it may be the key opening the way for certain wide crosses between the species of *Beta*. The results from European work that are beginning to come in concerning the productiveness of triploids, certainly demand thoroughgoing exploration with American varieties. As indicated, the research in the United States has simply shown that polyploidy itself is not an automatic way whereby production may be increased. The finding of highly productive polyploids and their use, either as tetraploids or as triploids, have not thoroughly covered the possibilities in this field of research.

The control of certain serious diseases by resistant varieties, although affording a fair measure of assurance against crop failures, is certainly not a closed matter, because losses are still heavy. We may forecast that the improved sugar beet in the next two decades will incite wonder as to why present-day varieties once were prized. As said, control of virus yellows and sugar beet nematode is still to be achieved, but evidence given by Coons (1952) and Rietberg (1954) indicates that disease resistance breeding may be effective against virus yellows. There are indications also that breeding research may be useful against the sugar beet nematode (Rietberg, 1954).

Once certain morphological and disease resistance goals are gained, or even some half-way point is reached, there remain the great problems concerned in improving the sugar beet as a living machine. There is a job of making it a better, more efficient sugar producer; reducing its complement of harmful nitrogen; removing the melassigenic elements; in short, as physiological research explains the metabolism of the sugar beet, the breeder must be ready to build on these findings. The sugar beet needs to be improved in storagability, both with respect to resistance to decay and oxidation rate. These fields of research as investigated by Gaskill (1952b), Stout and Smith (1950), and Nelson and Oldemeyer (1952) already are showing great promise. In another approach to sugar beet improvement, the results given by Wood *et al.* (1950) indicate that tolerance to cold exposures may be increased, the seedlings which have survived subfreezing temperatures giving progenies with greater cold tolerance than the parental material.

The jobs yet to be done serve to make us humble in appraising the improvements that have been registered. The advances that have come since the White Silesian beet was picked out by Achard give encouragement in facing the problems of the future.

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Green Manuring Viewed by a Pedologist

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CONTENTS

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I. Ideas and Concepts

1. Introduction

Green manuring, as discussed in this paper, does not refer to practices and methods of growing crops for purposes implied by the term. In the main, the object is to assess effects of these practices and methods in the light of pedology. In general, these effects are reflected in soil-plant relationships more or less alike qualitatively, and less so quantitatively, with any type of organic matter that finds its way incidentally into the soil or is intentionally placed there, such as sod crops, residues of cover crops, straw or stubble and roots of grain crops, top growth and roots not harvested, such as corn stalks, vines of peas, beans, potatoes, and tomatoes, and organic material brought in from the outside, such as barnyard manure, peat, by-products of the food industries, sawdust and wood chips, sewage sludge, composts, wool waste, and others.

Thus, whereas green manuring per se is the focus of the discussions, the theories advanced and principles evolved may be applied in total or in part to methods of utilizing any kind of organic matter. These theories and principles stem from the natural laws governing the processes of soil formation. This is the pedologic approach in the study of green manuring in the respective zonal soil types, subtypes, and varieties of these.

2. Historical Analysis

Pieters' volume (1927) *Green Manuring*, being the most comprehensive presentation on the subject, is universally quoted. Indeed, it presents a review of the history and development of the many phases of the green manure problem, going back to practices in China, 1134 B. C.

In the preface of his volume, Pieters states: "The value of green manuring lies in the fact that organic matter is worked into the soils." Trunz (1911), Stoklasa (1926), and Wöhlbier (1931), covering investigations on green manuring published in German, stress this very same fact.

Pieters and McKee (1938) have concluded "that in the main the object of green manuring must be to maintain rather than to increase the quantity of organic matter in soils." Standard texts on soils, agronomy, and horticulture repeat these statements. The men on the land have accepted the practice. Some have succeeded better than others; some have failed; and most of them have been asking one and the same question: "You experts speak of increasing the store of organic matter in the soil, or of sustaining a suitable amount of organic matter,

but how can this be accomplished? And if so, is the scheme practical and economical?"

The terms *suitable amounts* of organic matter or *maintaining the quantity* of organic matter in the soil are vague and confusing. Alert students exposed to the first course in soils have never failed to raise the question when reading the standard texts on soils or the barrage of propaganda by the soil conservation zealots and organic matter faddists: "But what do they mean by these terms? Do they imply the organic matter content of virgin soil? But that has been shown to be impossible."

Pieters and McKee (1938), who have been wrestling with the problem for many years, are somewhat dubious of the chances of increasing the soil organic matter content by green manuring. They state that "no very large additions of the soil organic matter can be expected from turning under a *single* green manure crop." Do they expect to increase the organic matter content of soils by turning under more than a *single green manure crop?* And again, is a long-term practice successful and practical?

As shown presently, Pieters and his followers (who scooped assiduously the rich well of Pieters' assembled and systematized data) failed to appreciate the implications of the status of the organic matter component of soils in various climatic zones with reference to the functions of green manuring. Pieters does speak of the soil and climate variations as factors in green manure practices, primarily with reference to the type of green manure crop best suited, as determined by trials in different parts of the world.

Originally, green manures have been used for their fertilizer value. They were not looked upon as a substitute for animal manures, even though their value was recognized as equal to these. Green manuring was not considered an expedient to increase the organic matter content of soils. In the history of green manuring these phases are a recent development, appearing on the scene with the advent of specialization and mechanization of agriculture.

Albert Schultz (1897) from Lupitz, Germany, better known as Schultz-Lupitz (spelled Schulz in some publications), is recognized as a pioneer in modern green manure practices. After about two decades of unsuccessful experimenting with various green manure crops, including clover, he stumbled on the lupine, and that gave excellent results. A perusal of his work shows him to be a disciple of Liebig's mineral theory. He applied PK salts only, expecting nitrogen from ammonia in the air, as erroneously postulated by Liebig. His failure with clover was later explained (his experiments date back to the 60's of the 19th century) by the acid condition of the soil. Lupines, being tolerant to acidity,

made up for the nitrogen deficiency. Thus, the reputation of green manuring in modern times has been re-established by way of solving a nitrogen-deficiency problem.

With the advent of mechanization and specialization in agriculture, farmers had been alerted to the specter of farming without animal manure and of the impending depletion of soil organic matter. These lamentations came from the popular soil chemists, the agronomists who then dominated the field of soil fertility, the group of soil microbiologists who monopolized the organic component of the soil (in test tubes, petri dishes, and tumblers), and the scientific agriculturists, as exemplified by the illustrious Hopkins, Hall, Van Slyke, Lipman, and their like.

A perusal of the writings of these specialists on green manure, animal manure, cover crops, and additions of other sources of organic matter reveals the development of a soil organic matter mentality complex. Most soil productivity problems have been reduced to a common denominator, the factor of soil organic matter. Failures of one kind or another, the lack of response to some mineral fertilizer treatment (which, by the way, has gained great popularity in the face of the loss of animal manures), or any ill of the soil has been explained by the lack of organic matter. Unsavory by-products of this mentality are many. Two well-known examples are: (1) the ill-famous plowman's folly of renouncing scientific methods of mineral fertilization and substituting trash; (2) the organic farming fad discussed by Joffe (1952).

Some wrinkles in the practice of green manures have been ironed out during the intensified program carried out in the early part of our century. Thus, failures resulting from plowing under green manures of a high C:N ratio have been generally eliminated by supplementing with a mineral source of nitrogen. Notable advances have been made on methods of handling green manure crops and the adaptation of species to various climatic regions. These topics are covered by Pieters (1927).

In view of the popular successes of green manuring per se and in combination with mineral fertilizer, the issue on the relative merits of green manure and animal manure lost its edge. Still, reports may be cited showing animal manures as superior to green manures and vice versa. Farmers who grew up in an environment of farming with manure (and there is already a generation of vegetable growers who farm without animal manure and who do not know how to use animal manures) will still maintain that there is no good substitute for animal manures.

The great debate on the factors responsible for the effectiveness of green manuring is associated with the relation of different sources of

organic matter to the vague concept of improving the soil and specifically to the problems of soil structure, soil moisture, and residual effects, and the befogged issue of increasing or maintaining the organic matter content of the soil. Reports on the items mentioned are conflicting, and data may be cited supporting any claim.

Fuel to the flames of confusion on the organic matter problem has been added as a result of the activities of the Soil Conservation Service, originally known as Soil Erosion Service. In their propaganda to get the public (or the Congress) conscious of the problem, the evangelist zealots of the Service had raised the specter of doom resulting from the depletion of soil organic matter and the necessity of increasing its content (they were not satisfied with maintaining the organic matter as looked for by Pieters and McKee and their like). The formidable contributions of the Soil Conservation Service in healing the scars of erosion have been dimmed, and confidence in the Service has been damaged by confused ideas on plowing under heavier and still heavier (which meant more mature) green manure crops and taking out from circulation cash crops and substituting continuous green manuring for a season or two in an attempt to increase the elusive organic matter content of soils.

It is generally recognized that a number of blind alleys exist in the evaluation of the mechanism of reactions involved in the well-established favorable effects of green manure, let alone in the causes and reasons for failures to achieve results or even for injury to crops following green manuring.

3. *Pedologic Analysis of the Green Manuring Problem*

a. Essence of Pedology. Pedology has advanced a series of basic facts and properties of soils stemming from interpreting the natural laws governing the evolution of the soil body. All soils, irrespective of their geographic position, are endowed with one and the same set of broad fundamental features in their constitutional make-up. By and large, these features are the expression of the over-all elements of climate. But, besides the broad fundamental features imparted to soils under different climates, they acquire within the respective climatic belts or zones, specific physical, chemical, mineralogical, and biological features which are an expression of the specificity of each climatic zone. These features assert themselves in a differential behavior and response of the respective zonal soil types to human activities, the so-called soil management practices. More precisely, the specificity aspects of the soil groups of the world are associated with the geographic distribution of the climatic belts or zones along latitudinal-longitudinal lines. Shifts noted away from these lines are caused by twists in the geomorphology

of the landscape, local climate, influenced by ocean currents (Gulf Stream), type and distribution of precipitation, wind direction and intensity, position of mountain chains, and other departures from normal of natural phenomena in any specific geographic setting.

b. The Zonality Principle. The pedologic concepts on the climatogenic nature of the soil-forming processes, enunciated by Dokuchaev, are a special case of the zonality principle operating in nature. This principle stipulates well-defined indices that characterize every animate or inanimate object or its or his behavior within the limits of the natural zones, chiefly climatic, and their associated phenomena. For example, in every climatic belt the zonality principle dictates group entities of soils, plants, animals, hydrologic conditions, mode of weathering of geologic bodies, and everything else associated with nature on our planet. These dictates produce more pronounced effects in some natural bodies than in others.

It is up to the investigator applying the principle of zonality to select those elements of the object or phenomenon and their properties and behavior that are a direct consequence of the specificity of the respective zonal characteristics, such as geology, physiography, climate, and ecology. Having recognized the effects of the zonality principle, the investigator may compare and correlate phenomena exhibited by similar objects in various zones and make appropriate deductions for his purposes.

So much for the generalized application of the zonality principle. We shall now examine its application to the subject of our immediate interests, the organic matter component of the soil and associated phenomena in relation to green manuring.

The organic matter component of the prevailing climatogenic and climatogenically subdued soil types varies in quantity, quality, and mode of decomposition in accordance with the zonality principle. These variations in the organic matter component in turn affect the properties of the soils and the value of green manures in soil management practices.

Soils in the chernozem zone top those of the other zones in quantity of organic matter. Soils in the zones of the semidesert and laterite-lateritic types contain the lowest quantity of organic matter. Intermediate between these two upper and lower extremes lie the quantity limits of organic matter of the soil types in the other zones: podzol, tundra, brown-chestnut, and those affected by orogenic, lithogenic, and hydrogenic factors, with the exception of the peat and muck varieties.

The humic acid group of the organic matter component of soils will illustrate the influence of the zonality principle on the quality of this

component. Thus, the preponderance of humic acid in chernozem and the saturation of its organic matter exchange complex with bases are in sharp contrast to the low content of humic acid, the high content of fulvic acid, and the prevalence of hydrogen ions in the exchange complex of the soils in the zone of podzolization. Knowing the variables in the quality of organic matter, one may speculate on the variable effects of the organic matter in these zonal soils with special reference to the probable behavior and functions of green manure crops and other types of organic amendments in the respective soil zones.

4. *Organic Matter and Green Manuring*

a. Introduction. The differential qualitative and quantitative properties of the organic matter component established for the respective soil zones clearly demonstrate that the mode of decomposition of organic materials in the various zonal soils differs. Pedologists have also shown that roots and tops of plants vary in their rates of decomposition. These few facts are cited (and many more will be brought up later) to illustrate the importance of relating effects of green manuring with the specific properties of the respective zonal soils.

Humification and mineralization (decomposition of organic matter) and associated reactions are most intense in the zone of laterization. Actually, mineralization rather than humification dominates the reactions of organic materials in the zone of laterization. These reactions are not as intense in the zone of podzolization and become still less intense, in declining order, in the chernozem zone, chestnut-brown and brown, and semidesert. Of the remaining soil types, some hydrogenic soils exhibit more humification than mineralization. The orogenic, lithogenic, and some hydrogenic types follow no particular order, but vary in mode of decomposition from the other soil types. A more extensive discussion of organic matter in zonal soils may be found in Joffe (1942a, b).

b. Soil Organic Matter Constants. One of the important broad pedologic features of soil types, their subtypes, and varieties is the constancy of their organic matter content. It is common knowledge that virgin soils have a higher organic matter content than cultivated soils and that it is practically impossible to maintain the organic matter level of virgin soils. It is, however, not appreciated that by changing the type of vegetation it is possible to recharge some soil types to a higher and others to a lower organic matter constant. Thus, by putting cultivated soils, originally in forest vegetation, into sod for two to three years, the organic matter constant may be raised above that in the virgin forest state. This higher constant may persist as long as the soil

is kept in sod. Similarly, by establishing a forest stand (shelter belts) in the grass country, the organic matter constant of the steppe soil may be lowered.

The simple pedologic fact of the constancy of organic matter in soils as dictated by the zonality principle was corroborated in an elaborate investigation by Jenny (1930).

Another important aspect of the organic matter constancy factor is that by incorporating huge quantities of manure or similar sources of organic matter, the level may be raised above the constant of virgin soils and kept there as long as the practice is maintained. However, as soon as the practice terminates, the level of organic matter drops to the constant of cultivated soils. *This constant cannot be lowered, no matter what system of soil management is followed.* In other words, there can be no depletion of organic matter beyond the constant of these soils.

The dictates of the zonality principle on the low constant of soil organic matter in the zone of laterization have been challenged from time to time. A facet of this problem is to be found in Joffe's volume *Pedology* (1949b). Broadbent (1953) touches on this problem in his highly interesting review of the subject on the nature and properties of the soil organic matter component. In a brief discussion on the relation of climate and vegetation to the distribution of soil organic matter, Broadbent cites the attempt of Jenny to reconcile his observations on the status of organic matter in the soils of the tropics with his earlier theoretical deductions. Broadbent seems to favor the ideas expressed by Smith *et al.* (1951), who claim that "typical soil organic matter and N percentages and total quantities are at least as high in Puerto Rican tropical soils as in many of the best soils of temperate regions."

It would take us far afield to analyze the data of Jenny, Smith, and others to show that a high organic matter content in the tropics is restricted to some specific condition or factor of soil formation, such as hydrologic, orogenic, lithogenic, or human activity. From the writer's observations and study of soil conditions in Puerto Rico, it is obvious that, in the case of Smith's data, the factor of human activity and, in some areas of Puerto Rico, the lithogenic and hydrologic factors are responsible for the high organic matter content of the soils studied. Sugar cane culture and in a less degree coffee culture in Puerto Rico, with respect to organic matter accumulation in soils, are in the category either of sod culture or reversion to the natural forest state. In such an environment, as pointed out earlier, sod tends to raise the organic matter constant or maintain the constant of the virgin state. The probability of a rendzina-like and/or regur-like type of soil formation in Puerto Rico is not to be excluded from the picture.

c. Fundamental Proposition. On the basis of views expressed and on the analysis of the status of soil organic matter, the following proposition is derived: *green manures cannot be expected to increase the organic matter* content of cultivated soils in any soil zone. A corollary to this proposition is: *the principal benefits and functions of green manures do not stem from their quantity factor.* In other words, the widely accepted idea that green manuring can increase the soil organic matter content and maintain it is ruled out by the proposition expounded.

This proposition does not exclude chances for raising the organic matter content by adding sources of organic matter from the outside, such as composts, peat, by-products of food industries. Also, by keeping the land in the zone of podzolization in grass, as pointed out earlier, the organic matter content can be raised. These aspects of the over-all organic matter problem in intensively cultivated soils are special cases.

d. Organic Matter from Tops and Roots. In the modern history of green manure practices, crops supplying the largest quantity of top growth have been emphasized. This approach stems from the days when green manures were looked upon as a substitute for the dwindling supply of animal manures. Green manures and animal manures have been compared for their respective effects on crops and soil conditions. Here and there, the contribution of roots to the total soil organic matter has been considered to bolster the notion of the quantity factor of soil organic matter. The specific quality of roots in relation to their influence on crops and soil has scarcely been considered in the literature on green manuring.

Not until the development of pedology was it realized that the high organic matter content of chernozems is associated primarily with roots. This lone finding should have led investigators to draw some inferences on the differential role of tops and roots in the practice of green manuring. Regrettably, very few authentic data are available on the differential effects of the two components of plants in the system of soil conditions and plant growth in general, let alone with reference to green manuring.

From studies of different zonal soil groups, with chernozem as the standard of comparison, pedologists have inferred that soil structure stability is not favorably affected to any appreciable extent by the top growth, but by root activity. Moreover, it has been shown that beneficial effects noted from plowing under a heavy crop of top growth are not due to structure stabilization, but simply to an increase in total volume of the soil as reflected by volume weight determinations. In this manner, the pore space increases and it favors permeability, which property is mistakenly taken as an improvement in structure.

In general, reports on quantity of roots of the same species in various parts of the world have confused investigators not versed in pedologic principles. Variations in root growth in different soils have been vaguely recognized, and the causes behind these variations have not figured in the discussions.

Roots decompose much more slowly than top growth plowed under. This has been recognized early by pedologists and later by others. This behavior is probably associated with the chemical composition of the roots. Thus, when sod (primarily root growth) is plowed under in regions where green manuring is effective, there is seldom a negative effect. With sod, it is not essential to follow the precautions taken when a heavy growth of green manure is plowed under.

That roots seem to be the primary source of stabilizing agents for soil structure does not exclude entirely those from other sources, such as top growth of green manure crops, stubble, vines of crops, barnyard manure, and surface organic mulches. In evaluating the mechanism of reactions involved in structure stability we must also remember that many unknowns in the equation are still to be solved.

II. Green Manuring in Zonal Soils

1. Introduction

In the literature on green manuring, the over-all ideas on the causes, functions, behavior, and reactions associated with this practice (to be expressed collectively by the term *effects*) may be summarized under the following headings: (1) organic matter supply; (2) nutrient supply; (3) soil structure improvement; (4) moisture relationships; (5) residual value.

Which one of the effects of green manuring or which combination of these is beneficial or at times injurious to the succeeding crop, and what is the mechanism of these effects? These questions have been argued back and forth since the days of the Romans. In modern times, since the days of Schultz-Lupitz, this argument appears from time to time, but in the main it has been reduced to a discussion as to which and how one or a combination of these effects is of greater or lesser importance in the benefits derived by the succeeding crop. Evidence of the lack of a concordant agreement and of the existence of confusion and contradictory data may readily be found in the literature. Typical of this state of affairs is the fairly recent analytical review by Scherbatoff (1949).

Speaking on the efficacy of green manuring, Scherbatoff notes that "there is more than one school of thought on the cause of increased yields obtained. A commonly held idea is that the principal benefits

result from the increase in the nitrogen and humus contents of soils that comes from plowing in the upper parts of plants in a green and succulent state. Other advantages ascribed to green manuring are improved physical properties of the soil and conservation of soil moisture. In most writings of green manuring attention has been mainly concentrated on the decomposition of the green manure and the resulting effect on the composition of the soil." He cites investigations in South and West Africa by Faulkner (1934), Faulkner and Mackie (1933), and Haylett (1943), who claim that "'green manuring under the light soil conditions at Ibadan, Nigeria, benefits the crop not by virtue of its improving the nitrogen or organic matter content of the soil, by modifying soil moisture relationships, but by the mobilization of nutrients."

Introducing the divergence of views, Scherbatoff compares results "of most writings on green manuring" (that is, *on soils of divergent zonal soils*) with results from the tropics. In a pedologic analysis of the problem, it is brought out that the effects of green manuring operate differently in the respective soil zones of the world. For example, in the zone of laterization the effect on soil structure is negligible, whereas in the zone of podzolization and in transition zones this effect is of considerable importance. In the humid tropics and subtropics the nutrient supply effect follows a different pattern than in other soil zones with reference to source of supply, top growth or roots. The moisture effect is the determining factor in the total failure of green manuring in most of the pedocals. In the light of the zonality principle, with reference to the respective zonal soil groups, the apparent divergence of views, contradictions, and confusion prevailing in the literature disappear.

2. *Applying the Zonality Principle*

The excellent summary of Pieters, made more than 25 years ago, on the status of green manuring in some parts of Europe, Asia, the East Indies, and the United States, offers an opportunity to demonstrate the application of the zonality principles to clarify the problems of green manuring. Unwittingly, Pieters has applied this principle in compiling his data on the adaptability of specific green manure crops and their effectiveness in the different climatic regions of the country. He assembled the facts available in a climatic-geographic setting: The southern states, the North Atlantic seaboard (from Virginia to New Jersey), the northeastern United States, and Canada (including the Corn Belt), the Great Plains, and the Pacific Coast. This setting lends itself to a pedologic analysis.

By and large, the effectiveness of green manuring, as may readily be inferred from Pieters' data, varies as we move from the zone of

laterization, the southern states, through the transition zone from laterization to podzolization (the North Atlantic seaboard), and through the soils in the zone of podzolization proper (the northeastern United States, Canada, etc.). In the northern soil subtypes of the zone of podzolization reports appear on the ineffectiveness of green manure and even damage, or loss of revenue, from practices of green manuring.

Pieters includes the Corn Belt in the region of the northeastern United States. An examination of the scanty reports on green manuring cited by Pieters and those published since in Indiana, Illinois, and Iowa shows that the practices in this belt do not conform to the conventional system of green manuring practices of the southern states or North Atlantic states. In the Corn Belt, the so-called green manuring system calls for a legume sod crop in the rotation, usually clover. The objectives of sod, while related in some aspects to those of the conventional green manure crops, are chiefly to replenish the nitrogen and readily available phosphorus and perhaps to improve the soil structure. This system of sod culture aims to avoid the extensive use of mineral fertilization. In other words fertilization of crops in these areas is an economic problem.

Pedologically, the soils of the Corn Belt are a transition zone (referred to also as *interzonal*, not *intrazonal*) located west of the red-yellow soils in the southeast and of the gray-brown podzolic soils in the northeast, using Marbut's (1935) classification scheme. The organic matter constant of these soils is high. Green manuring or additions of other sources of organic matter, advocated by the alarmists on the exhaustion of organic matter even in these soils, are a risky practice, as shown in part III. The regeneration of the native organic matter in the soils under consideration comes about by way of roots and stubble. This source of native organic matter can be enhanced by judicious use of mineral fertilizer, chiefly nitrogen and phosphorus and perhaps also some sulfates of potassium and magnesium—a system now becoming standard practice in many areas of grain culture in the United States. Of course, here and there the introduction of grass sod will find a place, but far from the economically ruinous program advocated by the organic matter faddists and neo-Malthusians.

In the Great Plains region, Pieters found very little application of the green manuring practice. He states that, "as a rule, green manuring is not practiced in the Great Plains and repeated trials have shown that the practice does not pay on dry land. The green manure crop itself takes so much water that the following crop suffers and yields less than after fallow." The soils in this region are of the chernozem type. In it, the organic matter factor, as discussed in connection with

the Corn Belt, asserts itself more strongly. All in all, there is some justification for the accepted belief that green manures in these soils are generally ineffective.

For the region of the Pacific Coast, the discussion of Pieters offers little for pedologic analysis; it is devoted primarily to types of green manure crops rather than their effects. Still, Pieters has separated this area unwittingly from the point of view of the zonality principle. The Pacific Coast with its Mediterranean type of climate affords good chances for growing winter green manure crops, especially in the northern region. In southern California the paucity of total precipitation introduces a new factor, irrigation.

Soil management under conditions of irrigation in the arid and semiarid region of the temperate and tropical-subtropical climates is beset with many problems and difficulties. However, the general principles of the pedologic approach are applicable in solving the problems associated with the practice of green manuring in irrigating farming. The naturally favorable temperature factor of these regions, chances for the control of the moisture factor, and coordination of irrigation with natural precipitation offer an opportunity to regulate in a large measure the all-important soil organic matter phase. The dependable desiccating effects of the hot sun may be directed to simulate conditions approaching those of the chernozem zone. This speculative suggestion has its drawbacks, primarily in areas where the crops are grown exclusively with irrigation. The specificity of the profile constitution of these soils, the ever-present specter of salinization, and the necessity to flush the soils present specific problems. Outside of these areas, there is a chance for simulating in some measure conditions of the chernozem zone.

III. Green Manuring in Pedalfers

1. Zone of Laterization

In the zone of laterization green manuring has become a recognized beneficial practice. Its value is being questioned in areas of distinct intermittent dry and wet seasons. With some exception, most of the investigations in this zone deal not with the mechanism of reactions of green manuring. Efficacy of green manuring is evaluated in terms of yield increases.

a. Organic Matter Supply. No other soil type than those in the zone of laterization reflects more forcibly the validity of the proposition and corollary, mentioned under Section I, 4*c*, on the futility of trying to increase the organic matter content of soils by green manuring.

None of the reports on green manuring in the South cited by Pieters offer valid proof of having increased the organic matter content of soils. Neither do later reports from this geographic area provide evidence of successful attempts to accomplish this. Thompson and Smith (1947) and Thompson and Robertson (1953) in Florida, and Ware and Johnson (1951) in Alabama find it "difficult to maintain and even more difficult to increase the organic matter in southern soils." Ware and Johnson have battled with this problem since 1941. Even though they have recognized the difficulty of increasing the organic matter content of soils, they show no reluctance to repeat their futile attempts. Were they aware of the zonality principles governing the constancy of the organic matter component in the respective zonal soils, they would have given up their vain efforts in this direction.

To bolster their waning hopes of increasing the organic matter of soils in Alabama, Ware and Johnson find solace in reporting increases when animal manures, with or without green manure, are added year in year out. As shown presently (Section III, 1*e*) residual effects of green manure are of short duration in the zone of laterization. Organic matter "burns up" in this zone. The differences in the effects of animal manure and green manures are discussed by Joffe elsewhere (1949).

Bonnet and Lugo-Lopez (1953), after a period of 13 months, found no increase in organic matter after plowing under 5 to 10 tons of velvet-bean green manure crop followed by two corn crops. When 25 tons of the green manure crop was plowed under, some increase in organic matter was noted.

Theron (1936) questions the necessity of increasing the soil organic matter of the semiarid soils of South Africa where 5 to 6 per cent (a little over 2 inches) of the total precipitation (about 32 inches) falls during the dry season.

It is clear that in the humid tropics and subtropics and in other areas of this climatic belt where green manuring is beneficial to the succeeding crop, the chances for accumulating organic matter above the constant are nil. Attempts to gain such increases by green manuring are doomed to fail. Favorable effects of green manuring in the zone of laterization are to be looked for not in the accumulation of organic matter.

In the experiments conducted in the tropics of South Africa, as reported by Scherbatoff, "it made very little difference whether the green manure was cut at the end of the rains and buried green immediately, cut and allowed to decompose gradually before burial or allowed to grow until it died of drought before being dug. It was even found that

there was little or no loss in the succeeding maize crop if the green manure was burnt *in situ*. The only thing which seemed to make any substantial difference to the result obtained from green manuring was the complete removal from the field of the whole tops of the crop. This was due presumably to the loss of mineral matter." Sen and Baine (1952) in India and Orchard (1952) in South Africa substantiate the findings as summarized by Scherbatoff. Shepherd (1952) suggests beneficial effects in Rhodesia due to formation of antibiotics.

b. Supply of Nutrients. Green manure crops utilize the nutrients which without them would be leached, and mobilize other nutrients from the soil. As to how green manures make nutrients available, two viewpoints are current. The older one is that organic matter, as it decomposes, releases nutrients from the insoluble soil minerals. The more recent viewpoint does not exclude this source of nutrients, but it stresses the nutrient supply mobilized by green manures from the soil and released in the processes of humification and mineralization. All agree to the dictum that *green manure is of no value unless decomposition takes place.*

The release of plant nutrients from soil minerals is influenced by the specific characteristics of the respective *zonal* soil types which determine the intensity factor in the mode of decomposition of organic matter. This factor finds its highest expression in the zone of the humid tropics and subtropics, where the organic acids formed are readily converted by microbes and animal forms of life into end-products of decomposition, carbon dioxide, water, and mineral salts. The organic acids formed in the decomposition process have little chance to react with the soil minerals for any length of time. The inorganic acids, nitric, phosphoric, sulfuric, and carbonic, recombine with the bases released to form neutral salts and some bicarbonates. The copious rainfall in the tropics rapidly removes these decomposition products.

In the zone of laterization there is a paucity of primary minerals and an abundance of R_2O_3, the end-products of lateritic weathering. The latter serve as a protective coating on the few remaining primary minerals against an attack by the reagents of humification and mineralization. Thus, the circulation of nutrients received from this source is limited, and the burden of supply falls on the mobilized nutrients of the green manure crop itself.

The primary importance of the nutrient supply effect of the green manuring practice gains very strong support from investigations on burning the crop instead of incorporating it by plowing or disking. Faulkner and Mackie (1933), Faulkner (1934), Freize (1939), Mehta (1950), and Vine (1953) have shown that burning was just as effective,

and in some cases even superior, to the succeeding crop as the conventional methods of handling green manure crops. Vine's data cover a period of 20 years of experience in Nigeria. On the basis of these findings it was logical to conclude, as stated by Scherbatoff, that in Nigeria "the efficiency of green manure crops in accumulating readily available minerals as well as nitrogen is the primary function of green manuring."

Why ashing green manure crops is as effective as the conventional method of handling these, or why the latter practice is not superior to the former is not explained by Vine, nor by his predecessors. A rational answer to this and other questions lies in spheres thus far not explored. It is suggested that other factors, individually or in combination, are associated with the effect of supply of nutrients by green manure: (1) probability of nonsymbiotic nitrogen fixation; (2) role of roots; (3) disturbed balance of nutrients as a result of green manuring; (4) specificity of nutrients supplied by green manuring. Of these factors, nitrogen fixation may be tied in with the efficacy of burning the green manure crop.

(*1*) *Nitrogen fixation.* Even though ashing the crop, as reported in the Nigerian experiments, eliminates the nitrogen, the succeeding crop is not affected, in spite of the low nitrogen content in these soils. An analysis of the facts on hand suggests the reasonable deduction of effective nonsymbiotic nitrogen fixation in the zone of laterization. The probability of such a postulate finds support in correlating the newer knowledge of nitrogen fixation by *Azotobacter*, especially *Azotobacter indicum*, as pointed out by Starkey (1939), with the mode of organic matter decomposition in the soils of the tropics. With a sufficient moisture supply, organic matter in the tropics and subtropics decomposes very rapidly, sending into circulation a supply of bases and other mineral substances essential for *Azotobacter* metabolism. In the case of ashing the tops, the mineral substances are made available to the soil surface. This mode of supply is apparently more effective than the gradual release by decomposition. Undoubtedly the rise in pH due to ashing is a factor favoring *Azotobacter*. In addition, the reduced rate of decomposition of roots, in the absence of plowed-under top growth, affords a more extended period of chelating effects to capture the unavailable iron and phosphorus of the soil and retention of minerals by sorption. These elements are of importance to the nitrogen-fixing organisms.

Findings in recent years on nitrogen fixation by blue algae add credence to the postulate advanced. These algae thrive luxuriantly in the tropics, especially when the soil has an abundance of moisture. The

claims of Dhar (1942) and others on nitrogen fixation in the tropics by photochemical action present another angle not to be overlooked. Some investigators maintain that the nitrogen reported by Dhar is probably associated with the algae factor. Vageler (1938) refers to extra nitrogen supplied by the copious precipitation in the tropics.

While on a visit at the Yalta Botanical Gardens, Crimea, Russia, in 1928, Vil'yams, the biochemist in charge of investigations on cultural practices of vineyards, showed the writer data on the vigorous fixation of nitrogen by *Azotobacter* in the soils of the Crimea which had a very low nitrogen content and did not respond to mineral nitrogen fertilization.

(*2*) *Role of roots.* Ashing the tops of a green manure crop influences the mode of decomposition of the roots and of the native humus, the so-called soil organic matter left in the soil following humification (see paper by Russel, 1929, for a bibliography on this subject). Ashing eliminates some of the negative effects of plowing under green tops, such as the acceleration of the otherwise slow rate of decomposition of roots and of native soil organic matter referred to above. Broadbent and Norman (1946) and Broadbent (1947) have demonstrated that the carbon dioxide released and mineralization of nitrogen (20 and 60 per cent, respectively, according to Broadbent) originate not exclusively from the green manure crop but in part from the native soil humus. Löhnis (1926) had shown this to be the case long before the isotope technique made it possible to trace the reactions quantitatively. In tracing the movement and translocation of nutrients in the profile by the lysimeter method (data not published), it was found by the writer that a green manure crop of rye accelerates the decomposition of the native humus, as shown by the nitrogen balance in the soil inferred from the nitrate in the leachings.

McVickar *et al.* (1947) report roots and tops of a ryegrass green manure crop supplying 156 pounds of nitrogen 123.5 and 32.5 pounds, respectively, in the roots and tops. Assuming 5 per cent nitrogen in native humus, the probable source of nitrogen for the ryegrass crop, a total of 3100 pounds of it had to decompose to meet the demand. Allowing a high 50 per cent transfer efficiency for the 156 pounds of nitrogen from the native humus to the ryegrass crop, 6200 pounds of native humus had to be decomposed. The fallow plot contained 40,000 pounds of organic matter (presumably in the Ap) at the end of the four-year rotation. Thus, more than 15 per cent of the native humus had to decompose to deliver the necessary nitrogen for the ryegrass crop.

Of course, the last ryegrass crop in the rotation had at its disposal the residues of the previous cover crop as well as the crop residues of

the harvested corn crop (nothing is mentioned as to how the corn stalks were disposed of). If we examine the status of organic matter in the ryegrass plot, we find that it yielded in the spring of 1946 (apparently the last year of the experiments) 9653 pounds of roots and 2441 pounds of tops, in all 12,094 pounds of dry matter. In April of 1946, the total organic matter content of the ryegrass plot amounted to 46,000 pounds. Assuming that the plots were uniform (a dangerous assumption for coastal plain soils) and that the residual effects of four years crop rotation were of minor consequence (a plausible assumption for the coastal plain), it is reasonable to conclude that the bulk of the extra 6400 pounds of organic matter came from the last ryegrass cover crop. It indicates that the last crop of ryegrass tops (2441 pounds), equal to about 25 per cent of root growth, enhances the decomposition of the roots. This condition puts a demand for nitrogen which has to come from the stable native humus. The newly formed humus contains readily available NPK contributed by the flora responsible for the decomposition of the old native humus which is ordinarily not touched by the normally prevailing flora. This process is probably responsible for reports of decreases in soil organic matter after green manuring.

Ashing green manure tops favors a balanced supply of nitrogen, inasmuch as the C:N ratio is not disturbed by this practice. Since roots decompose more slowly than tops, even in the zone of laterization, but still at a higher rate than in the other zonal soils, the rate of supply of the succeeding crop compares favorably with that when the crop is dug in. Vine's (1953) data on the nitrate supply under the methods of handling green manure (ashing or digging in) are of interest in this connection.

During the early stages of the maize crop grown after ashing or digging in green manure, the soil of the latter treatment had 80 to 90 p.p.m. of nitrate-N during May (presumably in the plowed layer). This amounts to 1000 to 1150 pounds of $NaNO_3$ equivalent per acre (2 million pounds in 6⅔ inches of soil). The burnt plots (ashing) had 182 to 75 pounds of $NaNO_3$ equivalent. Thus, the maize crop in the dug-in plots was at a disadvantage in its early stages of growth because of the excessive supply of nitrates (Vine does not give data on the NH_3 content). Besides, the rate of supply of phosphorus, potassium, and other nutritional elements may have caused unbalanced ratios, let alone the other disturbances which are to be mentioned presently. On the other hand, the burnt plot was in good balance. The roots kept up a slow but steady rate of supply of nitrogen and other mineral nutrients, and the succeeding crop thrived well. In June, the nitrate content dropped. Heavy rainfall undoubtedly had caused some leaching of the nitrates.

By then the crop had put a higher demand on the supply of nutrients, and it is probable that the supply was not there. Unfortunately, Vine's compiled data give no figures on the movement, translocation, and distribution of nitrate in the profile. The low nitrate content in the surface soil is no criterion of the loss of nitrates. Lysimeter studies by the writer supplemented by analyses of soil-water extracts, show that the nitrates removed from the A_1 horizon or the Ap layer do not always indicate a total loss, if the soil is heavier than a loamy sand. Even in this soil texture the retention of nitrate and other ions is possible, if there is a normal B horizon. Very frequently the nitrates are translocated to the B horizon. In his case, deep rooting conditions, which are better in the zone of laterization than in the zone of podzolization, are helpful to the crop. This phase of the subject can stand some fruitful investigations.

Some advantages of ashing versus digging in the green manure crop are also possible and even probable by virtue of supplying the desirable source of energy (slow decomposition of roots) and the suitable mineral salt medium for Azotobacter and Clostridium (the latter operating more effectively during the wet periods of the growing season). This phase of the problem also offers a fertile field for study.

In evaluating the relative importance of tops and roots in the zone of laterization we are to remember the results obtained in Nigeria, which show that removal of tops did reduce the yield of the succeeding crop. This adds more evidence that the effect of nutrient supply is the most important one in the tropics. Whether the loss of nutrients by removing the tops can be made up with mineral fertilizer has not been established. Since ashing is helpful, additions of mineral fertilizer should act the same way.

(3) *Disturbances caused by green manuring.* A generally recognized disturbance manifests itself in an upset balance of the C:N ratio when straw or a nonlegume crop is plowed under. Heavy crops of legumes frequently cause the same disturbance, especially in heavy soils. In the zone of laterization, this undesirable feature does not last as long as in the zone of podzolization, where the time period for organic matter decomposition is much longer. Of course, the negative effect of a wide C:N ratio can be easily offset by adding mineral nitrogen. With exceptions, this remedy is not a must in the zone of laterization. The crop should not be allowed to grow big, whereby more difficultly decomposable organic constituents form. The rapid decomposition of young plants and their higher nitrogen content adjusts the C:N ratio before damage is done to the succeeding crop. The probability of nitrogen fixation referred to earlier should be recognized in C:N ratio adjustments.

From the point of view of C:N ratio disturbance, burning the crop (ashing) in this zone, although it involves a loss of nitrogen and other desirable elements, appears to be a positive factor. Grazing the crop and harvesting it for hay, grass silage, or mulching materials are also positive expedients in adjusting the C:N ratio.

A disturbance not generally recognized is the accumulation of carbon dioxide and simultaneous reduction of oxygen in the rhizosphere. This condition may become serious during the period of active humification of the green manure. During this period, the ensuing crop is subjected to a very uncomfortable environment. It has been shown by Lundegardh (1931) that above a concentration of 0.2 per cent carbon dioxide most crop plants begin to suffer.

Tomatoes, celery, and other crops in New Jersey planted soon after plowing under a heavy green manure crop or fresh manure have been ruined by hydrogen sulfide and methane. Such cases have been encountered by the writer even in the sands or loamy sandy soils of the coastal plain of South Jersey, where decomposition reactions during the summer resemble those of the humid subtropics. Excessive precipitation during the period following the plowing accentuates the formation of the sulfide and methane. An effective remedy against this disturbance is shallow plowing, especially the heavier soils, where an abundance of rainfall is expected. However, in the zone of laterization this disturbance is mitigated by the highly favorable conditions of humification and mineralization, but it should be recognized.

Ware and Johnson (1951) report that rye was not as effective as vetch for green manuring even when the nitrogen factor was adjusted by adding mineral nitrogen. Harvesting the rye has not adversely affected the succeeding crop. It is evident that disturbances other than the C:N ratio have entered the picture.

It may not be amiss to reflect at this point and compare the cultural methods in the periods before and after mechanization of tillage operations. The writer remembers well in the days of 1909 to 1911 plodding behind a plow drawn by a fairly good team of horses, trying to *plow under* a dressing of 30 to 40 tons of cow manure. Seldom did we succeed in accomplishing it. Most of the time the manure would be *plowed in,* or rather mixed with the surface 3 to 5 inches of soil.

This manner of incorporating manure had the advantage of excellent aeration. Changes of air through the surface 3 to 4 inches are more frequent than in layers below that depth. A high redox potential is easily maintained for decomposition of added organic matter, with no danger of hydrogen sulfide and methane formation. Besides, the rate of decomposition is reduced by virtue of rapid drying of the surface 2 to 3

inches of soil. This mode of decomposition offers a steady rate of supply of nutrients, the cardinal effect of manuring, throughout the growing season, with fewer chances of loss by leaching.

When the tractor appeared on the scene to turn a furrow 90° to 180° to a depth of 6 to 10 inches, large quantities of manure found their way in the layer below the surface 3 to 4 inches, producing anaerobic conditions and bringing about the disturbances described. Plowing under a green manure crop or barnyard manure to such depths and turning a furrow 180° are therefore to be avoided. Again, precautions are essential. Even in the zone of laterization these disturbances may become a problem.

Burning the crop eliminates the dangers enumerated. It should also be possible to accomplish similar results by harvesting the crop for hay, grass silage, or some other purpose and to replenish the loss of nutrients by adding mineral fertilizer.

(*4*) *Specificity of nutrients supplied by green manures.* Except for nitrogen which legumes add to the soil, green manure crops do not add nutrients directly, but contribute some indirectly by retarding or obviating losses by leaching. Another nutrient added by green manures, but generally overlooked, is carbon dioxide released for the succeeding crop to utilize in its photosynthetic activities. No experimental data are available to evaluate this possibility. From evidence on supplementing the supply of carbon dioxide to a growing crop, the probability of benefits from the release of carbon dioxide by green manuring is justified.

The principal beneficial effect of green manuring is the mobilization of the conventional nutrients from the soil and their return to the succeeding crop in a balanced form, readily available. Besides, the crop also returns the known and unknown so-called minor elements and other vital substances synthesized by plants, such as vitamins and hormones.

It is true that mineral fertilizer can furnish substitute for the nutrients green manure crops may supply. Experiments have proved this. Still, one may speculate on the other known and unknown benefits green manures contribute which mineral fertilizers cannot supply.

c. Soil Structure Improvement. A careful perusal of the literature reveals vagueness if not misconceptions on the effect of green manuring on soil structure. This circumstance and inadequate methods of determining quantitatively respective size aggregates or structural units have added to the prevailing confusion.

Contributions on soil structure in general and more so with reference to green manuring display poor orientation on the mechanism of the two elements or agents of structure formation: (1) binding, and

(2) stabilizing. To form structural aggregates, the individual units of the soil separates—sand, silt, and clay—have to be bound and then stabilized. It is known, but not thoroughly appreciated in certain circles dealing with the subject, that clay is the principal binding agent and organic matter in association with divalent (primarily calcium) and trivalent cations is the principal stabilizing agent. It is not uncommon to find reports of experiments showing improvement of soil structure by the addition of organic substances to sandy soils containing practically no clay, or not enough clay, to bind the individual particle-size units. Sand grains temporarily mechanically bound by some ever-present gluelike substance in decomposition products of organic matter are misconstrued as soil structure. No one as yet has shown that organic matter itself can play the part of binding agent in soil structure formation.

In the zone of laterization, the mode of decomposition, as pointed out earlier, dictates a low organic matter constant. On the other hand, R_2O_3 is in abundance. With the low level of calcium and the abundance of moisture in these soils, very little of the possible Ca-humates formed may persist. At the same time, this reaction retards the immobilization of humates by the R_2O_3 because of their low dissociation constants. This does not preclude the formation of some humates of iron and aluminum, and perhaps also of manganese. However, the paucity of organic matter in general also puts a low limit on the formation of such humates.

The lack of plasticity of soils in many areas in the zone of laterization is attributed to the coatings of R_2O_3 over the clay-bound particles. It was therefore suggested by Joffe (1949) that the structural stability of the soils in this zone is due to the R_2O_3 gels which upon dehydration reduce the plasticity of the clay.

Evidence is meager on improved soil structure by green manures in the zone of laterization. The same holds true for evidence on the ineffectiveness of green manures to improve soil structure in other soil zones. Martin (1944), working in Uganda, reports no improvement of soil structure by green manures with or without lime. These results, in his words, are "in direct opposition to those of Tyulin and Ilmenev." Martin, not aware of the zonality principle, did not realize that Tyulin and Ilmenev conducted their experiments in zonal soils in which organic matter is the principal stabilizing agent of soil structure. Bhowmick and Raychaudhuri (1953) from India conclude that there is no convincing evidence that organics have improved soil structure.

In the tropics and subtropics, the over-all specific processes of soil formation, apart from the broad fundamental processes inherent in all soil zones, introduce factors not recognized thus far or the significance

of which is not appreciated with reference to the effects of the organic component of soils. These specific processes undoubtedly tend to modify the course of reactions. In the tropics, these processes and conditions tend to lower the over-all negative charge of the soils and even impart a positive charge. In such a soil system the protective (or chelating) action of soluble organic colloids on the movement of R_2O_3 is at a minimum or ceases to function. Besides, the electrokinetic potential in the soil system of the tropics precludes the movement of R_2O_3 and no organic matter accumulation takes place in the lower horizons as it does in the zone of podzolization.

In the zone of laterization where a distinct dry season prevails, the R_2O_3 gels, together with the soluble organic colloids that might be associated with them, upon desiccation attain cementation properties which give rise to new formations. It is suggested that the buckshot structure noted in the zone of laterization is one of these new formations. Leaching effects that follow the dry season and intermittent desiccation and wetting periods may have something to do with the smooth surface of the buckshot.

d. Moisture Relationships. Ever since the inauguration of modern practices of green manuring it has been recognized that soil moisture is one of the factors determining the expediency of these practices. If a green manure crop is plowed under when the soil is deficient in moisture, its slow decomposition and accompanying disturbances extend the unfavorable conditions for the succeeding crop over a long period of time. This quality prevails in soils of the humid temperate zone of forest and adjoining grass country, of which more is to be said presently, but it is not apt to arise in the zone of laterization where natural rainfall or irrigation provide an ample supply of moisture. Favorable temperatures always prevail in this zone for rapid decomposition, thus shortening the period of disturbance to a minimum.

Rapidity of organic matter mineralization in the humid tropics and subtropics makes the nutrient supply effect the outstanding positive feature of the green manure practice. However, this positive feature is accompanied by the negative one of leaching. To reduce the danger of loss of nutrients by leaching, a reduction in speed of decomposition of the green manure may prove a desirable expedient, providing it does not increase the havoc of disturbance entailed by slow decomposition.

By scheduling the plowing operations after the end of the rainy season, if such does occur, and if the timing does not conflict with the cropping schedule, the decomposition may be retarded by the paucity of moisture. During this period the organic colloids age, the soluble colloids become insoluble, and the insoluble become still less soluble, by virtue

of the reactions of irreversibility of such colloids due to desiccation. It should also be possible to accomplish the same effect by cutting the green manure crop, allowing it to dry, and only then digging it into the surface 3 to 4 inches. Short periods of wetting followed by extended periods of desiccation enhance the irreversibility of the colloids and reduce still more the rate of decomposition. Incorporation of a green manure crop so conditioned into the surface 3 to 4 inches should improve the friability of the soil and gain for it improved physical conditions.

Speculations of this kind lend themselves to experimental test. They stem in part from deductive reasoning on the chemical and physical reactions associated with the specific soil-forming processes in the chernozem type of soil formation. These speculations also find support in the friability of the surface soil attained by tillage practices in the pretractor days of farming with manure, as discussed earlier.

e. Residual Value. In general, residual values vary with the type of green manure crop grown or type of organic material added and crop following. As to lasting effects, the zonality principle governs, being long in the humid temperate climate and short in the tropics and subtropics. The time period varies not only with the zonal but also with texture and intrazonal characteristics: hydrogenic, orogenic, and lithogenic.

Reports from various sectors of the tropics and subtropics are scanty on this phase of the problem. Those from Nigeria and Uganda, as reviewed by Scherbatoff, are emphatic on the "burning up" of green manure in the tropics, with very little residual effect. Bonnet and Lugo-Lopez (1953) found no residual effect after the first crop of corn was grown following the plowing under of a velvet bean crop.

Reports on the red-yellow soils in the United States, which represent soils of a transition zone of laterization-podzolization, also indicate no green manure residual effects. Thus, Ware and Johnson (1951) in Alabama state that turning under a summer crop for fall vegetables has very little residual effect on the next spring vegetables. "On plots on which cowpeas had been turned under annually for 9 years, the average yield of spring vegetables, 3 years after the last crop was turned under, was practically the same as the check."

In Puerto Rico soil areas were examined which had received annually for several years hundreds of tons per acre of filter press cake (a by-product of the sugar-cane industry) besides the natural stubble and roots of the crops grown. As much as a thousand tons of this cake per acre in one year was incorporated into a sandy soil. This means about 30 to 40 per cent of organic matter in the surface 6⅔ inches of soil. Within two to three years, practically all organic matter was "burned up" and no residual value could be detected.

Any other source of organic matter involving a return of roots and other residues of crop growth should behave in a manner very similar to the conventional green manure crop. Outside sources of organic matter, such as peat, by-products of food industries, and sawdust and wood chips will not measure up in their effectiveness to that of green manures. The release of nutrients from some of these products is extremely small, and they are not balanced as are those of growing plants. Their value lies in some physical effects, such as increasing the volume of soil, which last as long as the bulk of the material persists.

Animal manures as an outside source of organic material are in a category by themselves. Since neither the positive nor the negative effects of green and animal manures are exactly alike, a comparison of these has been difficult. Investigations published on this subject give no preference to either of these two sources. In general, animal manures have a much longer period of residual value than green manure. In the zone of laterization the rapidity of decomposition would tend to reduce this value.

2. Zone of Podzolization

To follow the effects of green manuring in the zone of podzolization, it is pertinent to remember that it extends from the edge of the tundra, in both hemispheres, up to either the zones of laterization and chernozem, as in North America, or to the chernozem only, as in Europe. The effects of green manuring vary with the specific features of this zonal type, its subtypes, and varieties of these within the vast geographic stretch of their distribution.

a. Organic Matter Supply. Sprengel (1837, pp. 274–276), who is credited with the overthrow of the *humus theory*, in a discussion of organic matter accumulation in soils stated: "Where the climate is cold less ammonia and nitrates are formed in the process of organic matter decay . . . All organic bodies decompose and decay more slowly in cold climates than in warm climates. Manure therefore persists much longer in the soils of the cold climate and yet more of it has to be added."

In this statement one may recognize the operation of the zonality principle in the supply of organic matter in soils. However, this principle had not been recognized by Sprengel. Neither has it been appreciated by investigators dealing with green manures since then. It is obvious that Sprengel's observations with reference to manure are applicable in a large measure also to green manuring.

In northern Maine, Terman *et al.* (1948) report poor showing for green manures. They come to the conclusion that this is due to "the rather high content of organic matter in the soil of the experimental

area." Records may be cited of muck land in New Jersey, which contains as much as 20 per cent organic matter, and of peat land in Florida, reported by Neller and Daane (1931), responding favorably to green manuring. This makes one doubt the explanation offered for the irresponsiveness of Maine potato soils to green manuring.

Terman (1949) reviews the long years of experiments with potato rotations in northern Maine. He shows green manures capable of increasing slightly the organic matter supply of soils. "At Aroostock Farm, the content of soil organic matter, after 20 years of rotation of potatoes with green manure crops, was 5.15 per cent, as compared to 4.90 per cent in adjacent plots cropped every year to potatoes." Yields of potatoes have generally increased after the green manure crop in a two- or three-year rotation. Still, it is questionable whether it is economically sound to occupy the land with a green manure crop an entire growing season. Even growing peas as a green manure crop, which gives some return, is apparently not economic.

Besides the economics of the green manuring practice in Maine, the question is whether it can be scored as a full-fledged green manure system. Actually, a crop occupying the land a full growing season is another crop in the rotation. In the case of peas as the so-called green manure crop the difference between it and continuous potatoes is minor. In both cases a crop (peas or potatoes) is harvested and the roots and vines returned to the soil. From the point of view of adding organic matter to the soil, potatoes and peas differ little.

It is clear that we are dealing with a quasi system of green manuring. In other areas, a sod crop in the rotation is introduced, not for the green manuring effects (these are in part incidental), but as an expedient "to raise the level of soil fertility," or as "a soil-improving measure," or as a "means of increasing the organic matter content of the soil." It is not uncommon to meet with recommendations to keep the land in a succession of crops for a season or two to attain the aims referred to, with very little to show for the effort and expense involved. These practices, even though operationally related, are actually not bona fide green manure practices, which come in between growing seasons, or for a short period during the growing season, with the aim of attaining the effects under analysis.

A digression from the main theme of this paper involving effects of sod crops may not be out of place at this juncture. With such crops in the rotation, usually for a year or two, the prominent benefits stem from the functions of the roots. They contribute physical, chemical and biological elements which favor succeeding crops. Structure improvement and increase in volume of the soil mass and their attendant in-

fluence on drainage and aeration figure prominently as the physical elements. Slow decomposition of roots obviating the negative effects of top growth and the gradual release of balanced nutrients represent the sum total of the favorable biological and chemical elements and reactions. Abundant data are available to substantiate the aforesaid. A more recent investigation by Snider (1950) in Illinois may serve as an example. The soils used belong to the transition zone, between the degraded chernozem and that of podzolization. This practice is most effectively and profitably applicable to the normal chernozem zone, where the effects of a sod crop may last up to five years. Following the zonality principle the practice is less effective in terms of time in the chestnut-brown zone or zones, still less in the zone of podzolization, where the factor of economics enters, as illustrated in the case of the Maine experiments. This practice is of little value in the zone of laterization.

According to Terman (1949), "the organic matter content of fairly level plots of Caribou loam was not decreased appreciably in 11 years of continuous cropping to potatoes. There is no apparent difference between the tilth of the soil on these plots cropped continuously to potatoes for 22 years and the soil cropped in a 2-year rotation of potatoes and green manure [a crop not to be harvested, or partly harvested, as in the case of peas] over the same period."

The conclusion one may draw from the Maine experiments is that under conditions of the northern belt of the humid temperate climate a slight increase in the soil organic matter content may be expected—an effect alluded to by Sprengel.

In a cropping system where genuine green manuring may be practiced, as with orchards, small fruits, some truck crops, the same slight increase in organic matter content may be attained as with a so-called green manure crop in the rotation, not to be harvested. In sandy soils, where conditions for decomposition are more favorable, there is no increase in organic matter content. One may infer this from the Connecticut experiments cited by Pieters.

Adams *et al.* (1936) made a study of green manure on a sandy soil of the Sandhill area adjoining the coastal plain of South Carolina, where the processes of laterization and podzolization merge and either one may be detected. A legume crop in the rotation was plowed under in one case, and in another case the tops were removed and the stubble only plowed under. In both cases, a cover crop of rye and vetch was planted and plowed under in the spring for the succeeding corn or cotton cash crop. It turned out that the stubble method proved to uphold higher carbon and nitrogen contents than the method of plowing under the entire crop.

The reason for the difference between the two methods has not been clarified by Adams *et al.* (1936). It is suggested that when the tops are plowed under the decomposition of the roots and native humus is intensified. By the stubble method no such intensified decomposition of roots takes place. At the same time the slower decomposition of the roots gives a longer lasting period of the incorporated organic matter (stubble and roots) until it reaches the constant for that soil.

In general, efforts to increase the soil organic matter by means of green manuring have failed in the southern sector of the humid temperate climate. Sprague (1936), in a report from New Jersey over a period of years, states: "Green manures failed to maintain the supply of soil organic matter." Similar results have been reported by Blair and Prince (1941).

There are circumstances which may favor an increase of soil organic matter in the zone of podzolization (more so in the northern sector). Whether such an accumulation of organic matter is desirable is a different story.

In a three-year survey, 1938 to 1940, of tomato culture in New Jersey, the writer representing the Soils Department and V. A. Tiedjens of the Vegetable Division of the Horticultural Department of the Experiment Station have encountered ill-smelling residues of the rye or wheat green manure crop plowed under in well-drained silt loam, loam, and even sandy loam soils of Salem County. These residues could be found at the end of the harvest season in September, well decomposed by then. Similar observations have been made by the writer in fields of celery in Gloucester, Morris, and Bergen counties of New Jersey. In these cases the crops have suffered and yields were low. In soils with a tendency toward poor surface drainage, especially during periods of more than normal rainfall, the conditions and results described have been accentuated.

Several expedients have been advised to eliminate the stagnant soil condition due to the persistence of the organic matter residues. First, not to fertilize the green manure crop, except for an application of 500 to 1000 pounds of a 2:1 mixture of dolomitic limestone and gypsum and 100 to 150 pounds of sulfate of potash-magnesia salt (now available under the trade name of Sul-Po-Mag) per acre. Crops treated in this manner had deep and extensive root systems during the fall and early winter, and the top growth was kept down. A light top dressing of Na NO_3 early in the spring will bring about a rapid growth of tops if this is desired. The effect of keeping plants starved is well illustrated in Fig. 1, as reported by App (1954). He dealt primarily with sandy soils in the more southern sector of New Jersey, where conditions for the effects of

green manuring approach those in the subtropics. It is not at all improbable that by encouraging root growth, as suggested earlier, the system of fertilization through green manure crops (the method followed by App) would turn out to be more economical and less hazardous than when top growth is plowed under even in light soils, let alone in heavy soils.

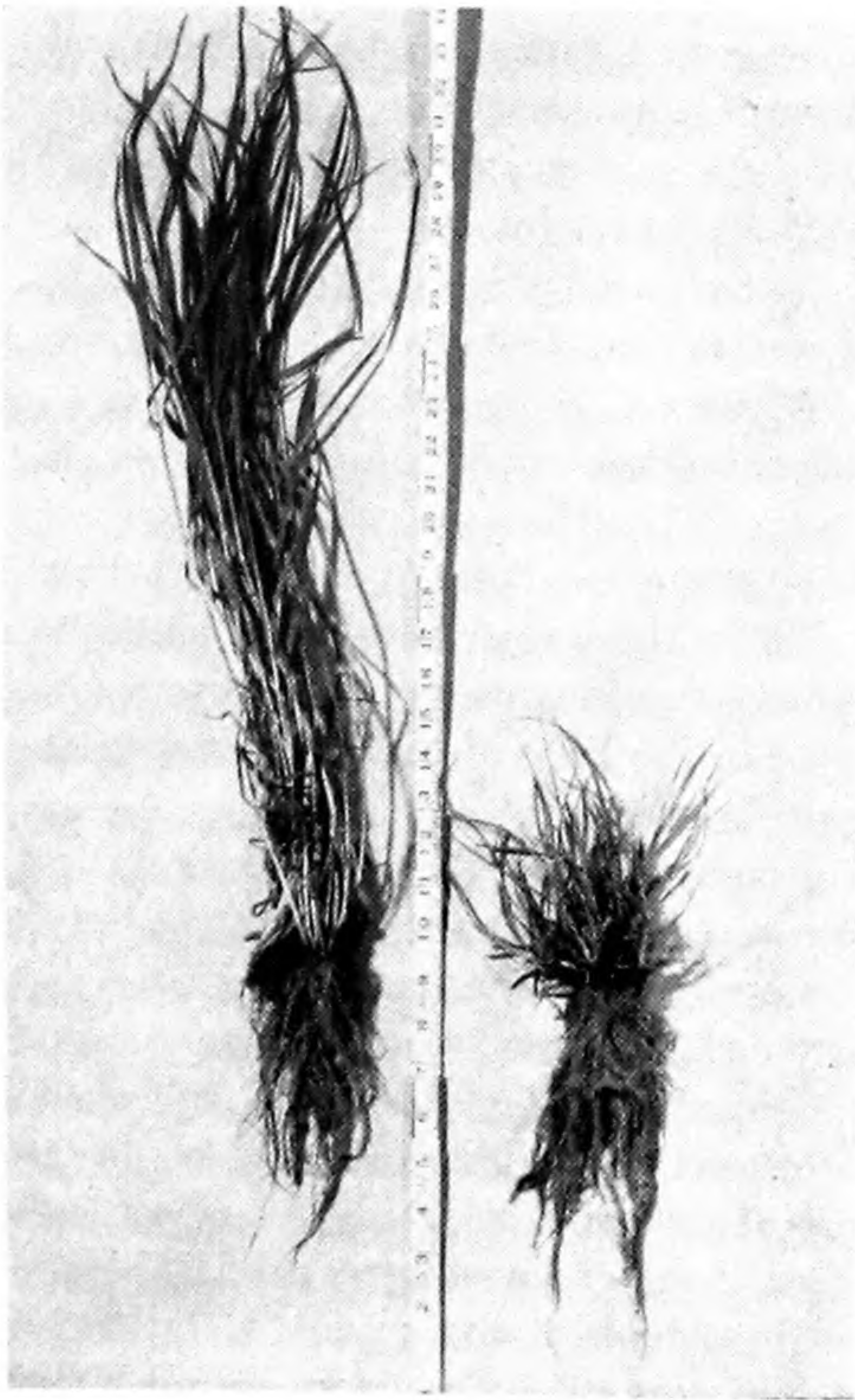

FIG. 1. A well-fertilized ryegrass plant and a hungry, starved plant. Note the more extensive root system in the starved plant. (Courtesy of Dr. Frank App (1954) of Seabrook Farms, N. J.)

Second, not to allow the top growth to go beyond a height of 8 to 10 inches and, if it is allowed to grow above that, the crop should be removed and used for some other purpose. It was hinted by the writer to some growers that this harvested excess might be burned if no other economic use of it could be made. No experimental evidence to prove this point is available, but from indirect evidence, as shown in the discussion with reference to the zone of laterization, there is a good chance

of getting the desired results, especially on soils that tend to suffer from poor surface drainage, even though the water table is not involved in this condition.

Third, not to plow deeper than 3 to 4 inches. This insures better aeration, more gradual decomposition, with no chances for accumulation of carbon dioxide or other undesirable products of the process of humification. Shallow plowing (deep plowing should be practiced in the fall when the cover crop is put in) may affect favorably the conversion of the soluble organic into insoluble colloids and reduce the ease of decomposability of the desiccated (at times) organic matter incorporated in the surface 3 to 4 inches.

Fourth, and this is commonly practiced, plow as much in advance of planting the succeeding crop as meteorologic conditions will permit.

b. Supply of Nutrients. As is the zone of laterization, prevention of losses of residual nutrients, mobilization of more nutrients from the soil mass, and their release when the green manure crop is incorporated into the soil represent the sum total of available nutrients. In the course of becoming available, these nutrients exert conditioning influences of positive and negative significance on the soil and crop. The influences are to be evaluated in the light of the specific reactions associated with the process of podzolization.

In the zone of podzolization, the decomposition intensity of organic matter is of lower magnitude than in the zone of laterization. From the point of view of supply of nutrients for the succeeding crops, this behavior is of positive significance, since the organic and inorganic acids linger on for a longer period of time and release major and minor nutrients from the soil mass. This intensity of decomposition reduces the rate of supply of nutrients released in the processes of humification and mineralization of the green manure itself. This too is of some positive significance, inasmush as the supply lasts longer. To accentuate this significance, the slow rate of nutrient supply may be compensated by adding small increments of mineral fertilizer. Without supplemental mineral fertilizer, this slow rate of supply may lose its positive significance, inasmuch as the growth rate of the crop would be reduced, and become one of negative significance. Large increments of mineral fertilizer seem to exert a negative influence. It is very probable, as shown presently (Section III), that this phenomenon is associated with the breakdown of the bulk of native humus, which in turn sends into circulation toxic organic complexes.

The expediency of adding mineral fertilizers opens by way of a detour the question of green manuring for intensive vegetable culture calling for heavy mineral fertilization. No specific studies of note are

reported on the problem of green manuring and mineral fertilizer supplements. From a personal communication by Dr. App, Seabrook Farms, New Jersey, where 25,000 to 30,000 acres of intensive vegetable culture are green manured, the method of supplementing the green manures, before planting and after plowing under, has not been worked out fully. In this case, heavy applications of mineral fertilizer associated with plowing under heavy top growth are likely to destroy the bulk of the native humus, introduce negative disturbances, and perhaps even reduce temporarily the organic matter constants inherent in the soils.

After the slight detour to return to the topic under consideration, it is worth speculating on favorable chelating reactions from acetic, citric, lactic, and other organic acids and complexes formed in the course of the prolonged period of the processes of humification and mineralization of the green manures. These chelating reactions may explain the favorable crop response reported when flour or rock phosphate was plowed under with green manure crops or with animal manures. Chelating reactions had probably something to do with the highly favorable effects of rock phosphate flour in the zone of podzolization in Russia, reported by Lebedyantsev (1940), and in the degraded chernozem of Illinois, reported by Hopkins (1910).

Thus, chelating reactions are to be considered in the category of positive significance from the point of view of supply of nutrients by green manures in all zonal soils, the degree of activity of these reactions probably depending on the time period organic complexes persist in the soil.

The enumerated points of positive significance with reference to the effect of supply of nutrients are in a large measure canceled by points of negative significance associated chiefly with disturbances caused by green manures, discussed presently.

As in the zone of laterization several other factors associated with the supply of nutrients by green manures have to be considered: probable nitrogen fixation, role of roots, disturbance in balance of nutrients, and specificity of nutrients supplied by green manuring. These factors assert themselves somewhat differently in degree, but not in kind, in the zone of podzolization.

(*1*) *Nitrogen fixation.* Since no experimental evidence is available on the effect of ashing the top growth in the zone of podzolization, the probable positive significance of nitrogen fixation is more speculative for this zone than for the zone of laterization. In view of these circumstances it is fair to postpone from consideration the factor of nitrogen fixation until experiments in this direction divulge the trends. By inference, on the basis of the zonality principle, the trends noted in the

zone of laterization should also be discovered in the zone of podzolization, probably in a lower degree of activity.

(2) *Role of roots.* Schultz-Lupitz, whose observations and experiments had been made on soils in the zone of podzolization, stressed the root effects as an important aspect of green manuring. In his records we find that potatoes after a green manure crop of lupines had extended their root system to a depth of 120 cm. against 40 cm. without lupines. Rye following lupines had had roots extending to a depth of 90 to 100 cm. against 40 cm. without lupines. This favorable effect on the succeeding crops, in terms of increased yields, may be attributed to the deposition of nutrients, especially nitrogen, by the lupines to greater depths in the soil, thus extending the feeding grounds of the crops.

Schultz-Lupitz worked with sandy soils where no compacted B horizon is apt to occur. Aeration below the plowed layer through the B horizon is generally good and roots may penetrate freely, unless toxic waste products eluviated from the A horizon should linger on in the lower parts of the profile.

In soils heavier than the sandy class, a compact B horizon, heavier in texture than the A horizon, is the rule in the zone of podzolization. In it, the accumulated R_2O_3 may send into circulation toxic limits of aluminum and iron, as well as of organic origin. Because of that, the moisture and nutrients usually present in the B horizon are not available to the roots of plants. Roots shun the B horizon in the zone of podzolization and concentrate chiefly in the Ap layer. Relatively poor structure stability of the soils in this zone is another stumbling block for root development. The naturally low pH values of these soils add no comfort to the root system.

Thus, the specific physical and chemical properties of the soil profile in the zone of podzolization are not suited for an extensive and deep root system. Still, although it is not possible to change the conditions inducing podzolization, there are always some means to offset some of the undesirable properties. Judicious methods of soil management may eliminate or at least mitigate some of the adverse conditions of poor rooting. Operations such as plowing, disking, harrowing, cultivating (with respect to timing, depth, and type of implements used) are to be adjusted to the specific zonal soil characteristics and variations within the respective zones such as texture and orogenic, lithogenic, and hydrogenic conditions.

Liming soils in the zone of podzolization, and for that matter also in the zone of laterization, is an expedient to overcome the adverse conditions for root penetration, in addition to neutralizing soil acidity. It

seems that the pH of the pedocals (from neutrality to pH 8.2) is well suited for proper acid-base equilibria from the point of view of root penetration and hence crop response. However, it is at times economically questionable whether one would be justified in maintaining such a pH range in the zone of podzolization.

The befogged issue of overliming, discussed by Joffe (1949a), may be raised in opposition to this without going into a theoretical discussion. The best rejoinder is the fact that in the pedocals, where the pH values are high, the problems raised by this issue are nonexistent. Moreover, many areas of soil on limestone parent material in New Jersey and adjoining states have a pH of 7.0 and higher. Not only do these soils not suffer from the alleged ills of overliming, but they benefit when limed. Besides, because of the immobilization of toxic materials as a result of the high pH values, deep rooting is common in these soils.

At the New Jersey Experiment Station, the experimental vegetable farm plots have been limed sufficiently within three years to raise the pH from a low 5.4 to 6.8 to 7.6 through the B horizon. As the pH has risen the roots of crops grown have extended their domain to depths of 20 to 24 inches. All through the period 1942 to 1954 none of the crops, because of their extensive root systems, suffered from the dry spells that occurred during these years. The earthworm population is high and their channels very stable and lined with carbonates of calcium and magnesium.

(3) *Disturbances caused by green manuring.* No other factor involved in the supply-of-nutrients effect in the zone of podzolization is as important as the one causing disturbances in the soil by green manure crops. The positive influences for nutrient supply are hampered seriously because of the disturbances.

The rapid decomposition of organic matter in the zone of laterization is a boon in avoiding many of the disturbances concomitant with the practice of plowing under a green manure crop. Thus, the generally recognized difficulty of C:N ratio is not acute in the zone of laterization because of the rapid rate of decomposition. On the other hand, in the zone of podzolization additions of inorganic nitrogen are essential whenever a heavy nonlegume green manure crop is plowed under.

No nitrogen, as a rule, is lost directly in the course of decomposition of the green manure crop. Losses of nitrogen by denitrification in heavy soils during periods of temporary saturation with water or in poorly drained soils of the zone under consideration may occur, more so in the northern areas. However, these are special cases which the student of soil should be aware of. In heavier soils, the disturbances by an excess of

nitrogen may cause lodging of spring grain crops or delay the setting of fruit in tomatoes. This phenomenon should be considered before nitrogen is added when a green manure crop is plowed under.

In the case of a green manure crop in the rotation, as described with reference to the Maine experiments, the time period between plowing under the green manure crops and planting the cash crop is sufficient to overcome the C:N ratio disturbance. As a matter of fact, plowing under this type of crop or any sod in the fall for a cash crop in the spring presents no problems in terms of disturbances. Whenever this system can be practiced, without introducing other negative influences, such as erosion, loss of some nutrients by percolation, and structure deterioration of the surface soil, the benefits of green manure in terms of supplying nutrients are as good as can be expected. Disturbances appear in full force when a green manure crop in rotation or a cover crop grown in the fall for green manure is plowed under in the spring. This holds true also for summer green manure crops practiced in the sector of the zone of podzolization where two cash crops can be harvested.

A disturbance more serious than the one of C:N ratio is excessive concentration of carbon dioxide and consequent depletion of oxygen in the rhizosphere. In no other soil zone is this disturbance apt to be as acute as in the zone of podzolization. Retardation of decomposition, because of abundance of rainfall and frequent anaerobic conditions in the soils of this zone, is the precursor of this disturbance. In the spring of the year when the soil has not warmed up sufficiently, with more than occasional saturations of the A horizon, with a cold and almost continuous moisture-saturated B horizon, and with sharp diurnal temperature fluctuations, the frequency and time period of anaerobic conditions causing a low redox potential may become very serious. This phenomenon has been observed in the course of the survey of the tomato industry in New Jersey, referred to earlier.

It is to be expected that the heavier the top growth of green manure, the greater the carbon dioxide disturbance and injury to the succeeding crop, even with good aeration. The increase in volume of the soil, due to the bulkiness of top growth, increases its porosity. This positive effect is offset by the disturbance just discussed. Investigations comparing peat and green manure proved the former to be at times more effective. Both sources of organic matter had improved the porosity, but the slowly decomposable peat gives no carbon dioxide disturbance, whereas the green manure does.

Other disturbances in the zone of podzolization, resulting from the slow decomposition rate of green manure, are associated with an unbalanced system of cations in solution and in the exchange complex,

and with the formation of toxic substances. A lowering of the pH, for some time in the course of humification, unbalances the Ca:Mg, K:Ca, and probably anion ratios. During the initial stages of humification, NH_4 ions, which may appear in excess when a legume crop is plowed under, may be toxic, as intimated by Crowther and Mirchandani (1931) and noted by the author in New Jersey tomatoes grown in heavy soils, particularly when the season was wet. The NH_4 ions also disturb the $K:NH_4$ ratio. These disturbances suggest additions of extra potassium and magnesium when the green manure crop is plowed under. Phenolic and other organic compounds, classed as toxic organic constituents, and toxic R_2O_3 are also likely to appear in this soil zone when a heavy green manure crop sets off the decomposition of the native humus.

Most of the disturbances are gradually eliminated as the humification and mineralization processes complete their cycle and stable humus is formed. Until then the positive influences of the nutrient supply are countered by serious negative influences. Recognition of these facts in the light of the zonality principle offers an opportunity to gauge the operations of green manuring in line with the reaction of the soil-forming processes specific for this soil zone and obtain the full measure of the effectiveness of green manuring. In practice we find in one and the same area green manures being at times a phenomenal success, good, medium, poor, and failures. It is obvious that in the latter case conditions have favored the negative against the positive influences.

The expedients suggested in the Section III, 2*a* on handling green manures in growing tomatoes in New Jersey are designed to favor the positive points and to mitigate or eliminate the negative points. Another expedient worthy of mentioning in this connection is planting a cover crop that would be winterkilled such as spring oats. This crop would provide deep and extensive root growth and dead top growth which would not produce the disturbances associated with plowing under green top growth.

c. Soil Structure Improvement. In the zone of podzolization the element of stability of aggregates and hence soil structure is not the R_2O_3, as in the zone of laterization, but the organic matter. As stated in the discussion of this topic for the zone of laterization, the highest degree of stabilization of aggregates is found in the chernozem zone. Organic matter is supplied by the extensive root system of the grasses in this zone. Upon humification, humic acid and other soluble organic complexes, together designated as humates, combine with the 60 to 70 per cent calcium generally maintained by the exchange complex, giving rise to Ca-humates which are soluble. Together with more Ca-humates

formed by the calcium and humic acid in the soil solution, these humates saturate the ultimate particle-size mineral units and their aggregates and enclose them into a membrane. Upon desiccation these membranes of Ca-humates become insoluble, acquire rigid elasticity, and do not slake when in contact with water. Undoubtedly, the reactions involved in forming the membranes are more complex than the patterns described. However, their formation and stability can be demonstrated experimentally. This stability factor in the chernozem may be inferred from the work of Tyulin (1946), who deals also with the stability of organomineral gels associated with R_2O_3.

In the zone of podzolization, distribution of roots is not extensive, and they are subject to more intensive decomposition than in the chernozem zone. Because of this and because of the inherent trends towards lower pH values in the zone of podzolization, the humates of hydrogen rather than of calcium prevail. Besides, the Ca-humates in this zone do not undergo the desiccating effects of the higher temperatures prevailing in the zone of chernozem. They thus remain soluble and are either leached or destroyed by microbial activity in the course of the more intensive rate of organic matter decomposition. The membranes formed are not elastic and are readily sloughed off. Slaking of clay-bound aggregates follows.

It seems logical that we should try as much as possible to simulate in the zone of podzolization the reactions nature has bestowed upon the soils in the chernozem zone. By withholding the nutrients, especially nitrogen, as pointed out earlier, roots of green manure crops are forced to extend their foraging grounds. One needs only to examine a cover crop which does not do well in terms of top growth, showing even nitrogen deficiency, to find how extensive the root system is. In Fig. 1, as mentioned earlier, it may be seen that the starved ryegrass has a far more extensive root system than the well-fertilized plant. It is of interest to note that Bruin (1953) discovered that the organic matter necessary for the maintenance of structure in Dutch soils is estimated to equal that of the roots and stubble of cereals. Martin (1926) in an extensive investigation comes to the conclusion that green manures increase yields, deteriorate the structure, and reduce the buffer capacity of the soil.

Additions of dolomitic limestone to soils to be green manured (even potato growers who are apprehensive of limestone, because of the scab problem, find that additions of a few hundred pounds of lime induce more extensive rooting) or, better yet, keeping these soils at a high level of calcium in the exchange complex would tend to form more Ca-humates which during dry spells may produce rigid membranes that

are not so readily slaked. Available lysimeter data at the New Jersey Experiment Station show that during seasons of prolonged droughts, the stability of aggregates is much greater, soil water extracts are not colored, and permeability increases to a very marked extent and may be effective for more than a year or two.

Top growth should be worked into the surface 3 to 4 inches. A much better practice would be to cut the top growth by a grass silage harvester or any kind of shredder, to allow it to dry to the stage of hay, and then to plow it in instead of disking it in. In this manner one might succeed in encouraging the type of stabilizing membranes found in the chernozem zone, at least through the surface 4 inches and perhaps an inch or two deeper. By keeping up a favorable Ca:Mg ratio in the exchange complex, the acidity following green manuring would be eliminated. More of the Ca-humates similar to those obtained in chernozem might form from the decomposing roots.

Excessive cultivation of row crops, or middles in orchards, where this practice is in vogue, should be avoided. It causes root pruning and pulverization of surface soil. The latter evil holds true for tilling soils with rototillers or similar implements which destroy the structural aggregates. Caking and baking of the surface soil follow these practices.

Incorporation of heavy top growth into the surface 3 to 4 inches may interfere with the seeding of fine seed. To avoid this, it would be best to remove the crop, or keep the top growth down to 3 to 4 inches. We must always be aware of the disturbances associated with plowing under heavy top growth depths of 6 to 8 inches.

d. Moisture Relationships. In the zone of podzolization, moisture conditions in the spring are generally not a negative factor. Incorporating top growth into the surface 3 to 4 inches of soil induces friability and eliminates the evil of crusting—a common phenomenon in the areas of intensive truck crop culture.

In this zone we also encounter the problem of getting water into the profile. The method of plowing in the green manure crop for friability mitigates this problem considerably.

From limited experiences with this method (plowing in 3 to 4 inches deep), it has been noted that decomposition of green manures is retarded, thereby reducing some of the disturbances discussed earlier. Apparently, drying of the surface soil in the late spring and early summer, a frequent occurrence in the zone of podzolization, causes the irreversibility of the organic colloids, referred to in Section III, 2*d*. Dry spells during the summer accentuate this reaction. If the deleterious effects of the process of podzolization were taken care of in the manner discussed by Joffe (1949) in Chapters VII and XI, roots would not tend

to concentrate in the surface portion of the Ap but would penetrate deep into A and B horizons—a cardinal positive factor in utilizing the moisture and nutrient resources of the entire profile.

Pieters points out that the effectiveness of green manuring is frequently reduced because of the depletion of moisture when a cover crop is plowed under. This factor begins to assert itself in the zone of podzolization. Droughty conditions are frequently induced by burying a green manure crop deeper than 3 to 4 inches. This shortcoming has been recognized for a long time. McCue and Pelton (1913) have conducted a questionnaire on the effect of crimson clover sod for tomatoes. Favorable reports were received from 119 farmers and unfavorable reports from 43 farmers. The latter group claimed that droughty conditions were responsible for the failures.

Pieters (1927) and later Russel (1929) have suggested that green manuring is not effective unless there is a minimum of 20 inches of precipitation. In a recent paper, Bernhardy (1954) doubts the value of green manuring in countries where the annual precipitation is less than 30 inches and the evaporation is high. The weakness of the limitation set by Pieters and Russel is reflected in the limitation set by Bernhardy, who appreciates the factor of evaporation. Besides, there are areas in the chernozem belt in the United States along ishyetal lines above 20 inches where green manure crops are not effective, except in special cases. On the other hand, there are areas in the zone of terra rossa with lower than 20 inches of rainfall where green manures are very effective. Conventional types of green manuring become less effective and even harmful (to the extent that manipulation of negative and positive disturbances is not successful) in the northern region of the zone of podzolization. A careful perusal of the Aroostook Farm, Maine, experiments will show that green manuring gives a meager response, and the rainfall is higher than 20 inches. Evaluation of soil-forming processes or the response of soils to any management practice in any soil zone cannot be successfully undertaken unless both elements of climate, temperature and mositure, are taken into account, as well as the type and distribution of precipitation.

e. Residual Value. In the zone of podzolization, crops that last longer in the soil, such as corn stalks, are suggested for green manuring. An enthusiast of increasing the organic matter supply has advised growing of locust tree seedlings for green manuring, without realizing that in the zone of podzolization this forest species gives no increase in organic matter content of the soil over oaks, maples, etc. It is questionable whether in properly managed soils the variations between one crop and another are significant enough to influence much the residual

value. Besides, the zonal soils, as well as the cropping system within the zone, put a limit to the types of crops one can use.

If we accept the view expressed that the supply of nutrients is in the final analysis the most important effect of green manuring, benefits from a green manure crop, in terms of nutrients, after the first season are quantitatively less in the zone of laterization than in the zone of podzolization. In this zone with its prolonged period of humification and mineralization, the residual value lies more in the increased buffer capacity of the soil, whereby the retention of *added* nutrients is extended over a longer period of time and leaching is thus reduced. Reports in the literature cite residual effects lasting from one to eight years. It is of course to be expected that in the southern sector of the zone of podzolization the period will be shorter. Light soils will retain a shorter period of residual value.

IV. Green Manuring in Pedocals

1. Chernozem Zone

As we leave the zone of podzolization and enter the grass country (steppe), the effects of green manuring as defined in Section II, 1, shift the order of their positions with respect to the reactions associated with this practice.

In the forest-steppe and gray-brown podzolic soils bordering the steppe, the process of podzolization is struggling against the invasion of climatic elements favoring the chernozem type of soil formation. On the other hand, the chernozem bordering the forest zone is being attacked by reactions favoring the process of podzolization, giving rise to degraded chernozem, the eastern prairie country of North America and the Amur region of Eastern Siberia.

Even if we were to assume that the organic matter supply effect of green manures is of importance, it is of minor significance in these soils, which are known for their high content and constant of organic matter. The soil structure effect does not present many difficulties. The naturally favorable structure (see Section III, 1*c*) of these soils may be restored by introducing sod and proper tillage operations. The residual value effect may be ignored, inasmuch as the normal replenishment of organic matter by the extensive root system of the cash crop, one of the outstanding characteristics of these soils, provides for this effect and for the high organic matter constant. The two remaining effects, supply of nutrients and moisture relationships, deserve to be considered a little more closely.

For row crops, such as cotton, corn, and sugar beets, green manuring

in the chernozem zone may be practiced to advantage, from the point of view of supply of nutrients, providing that the moisture relationships effect can be controlled satisfactorily. Benefits derived are in the category of chelating reactions, supplying phosphates (immobilized by the heavy circulation of calcium in these soils) and iron, and perhaps aluminum and manganese, made available in short supply by the well-known local action reactions. The well-balanced ratio of nutrients supplied by the green manure and the impeded decomposition of native humus are of positive significance.

With an abundance of moisture in this zone, decomposition of green manure may cause a serious destruction of the stable native humus, causing a drop in the organic matter constant and releasing toxic substances until such a time when this constant is re-established. It is probable that this disturbance may be obviated by supplementing mineral nitrogen when plowing under the green manure crop. An example illustrating a number of the reactions involved in the condition just described may be found in the report by Plice (1950).

For 16 years green manures have been turned under in the spring in a prairie soil of Oklahoma, vetch or winter peas on cotton and darso (sorghum) land, and cowpeas or mung beans on oat land. No information is given by Plice as to the time of plowing under the green manure crop, the yield of tops and roots, the time of planting the case crops, or the meteorological conditions. From climatological data on Oklahoma, as reported in the Yearbook of Agriculture (1941), it is clear that at Stillwater, where the experiments apparently have been conducted, there is a concentration of rainfall in the spring. And this is the clue to the lamentable results reported by Plice:

"Green manures have produced disappointing results. Sorghum and cotton have not been benefited and the yields of oats crops have been significantly reduced." Plice states in the summary: "These findings are mostly contrary to the general opinion on the ameliorating effects of green manure in soils and are here interpreted to mean that the green manure has had a degrading effect on the soil."

Plice (1950) made an extensive study on the soils of the green-manure and no–green-manure plots. His results are very enlightening and instructive, but he makes no use of his findings to clarify his disappointing results. He found that "the green-manure soil is lower in pH, available mineral nutrients, organic matter and nitrogen, bacterial and fungal population, field moisture capacity, nitrifying power, macro and micro aggregates, rate of water infiltration" green-manure soil has "a higher plasticity, volume weight, weak-alkali soluble organic matter

and nitrogen, redox potential, ammonifying power, toxic humic substances, potential and exchangeable acidities, and wilting coefficient."

The fact that the oats suffered more than the cotton is unquestionably due to their early time of planting. It had to follow soon after the green-manure crop was plowed under. The oats were subjected to the full impact of the disturbances described earlier. The sorghums and cotton crops had a later planting date and by then the intensity of the disturbances that had raised havoc with the oats had decreased. However, these disturbances had sufficient force to obviate the positive influences of supply of nutrient, etc., by green manuring and to encourage the negative influences, and the net result was negative as far as yield is concerned.

Nothing is mentioned by Plice as to the depth of plowing. Plowed under to any depth, under conditions of the usually wet springs in that area and in the presence of an initial high organic matter content, the green manure crops could not but lose most of their positive influences and exert in full force their negative influences on the crops following. The excellent analytical data provided by Plice, when subjected to review in the light of the reactions dictated by the zonality principle, explain readily his "disappointing results" and challenging statement that his "findings are mostly contrary to the general opinion."

If the green manure crops were removed (or dried and burned if not used for animal feed) or chopped up and worked into the surface 3 to 4 inches of the soil, the results would have been reversed. An inkling to this probability is apparent from the statement that "oats was superior on the non-green manure plots 75 per cent of the time." Why were not the results on the other 25 per cent of the time superior? A venturous assumption is offered: during this period, the spring rainfall must have been below normal and perhaps the top growth was not as heavy, and the record should show that the sorghums and cotton crops were much better with the green manure.

It may well be summarized that wherever the growing season is long enough, green manure crops have their place in degraded chernozem, as well as in normal chernozem where spring precipitation simulates the one described by Plice for the prairie soils of Oklahoma, and if properly managed. If, however, the spring precipitation is low, as is the case in large areas of the vast chernozem, the moisture effect may preclude the favorable effects of green manuring. When heavy top growth is plowed under it may introduce a cushion between the furrow turned and the adjacent soil. The result is a drying out of the furrow slice to the disadvantage of the germinating corn seedlings. Intake of

water under such conditions is impeded. This phenomenon has been observed and reported in the literature. Methods of handling it generally consist of disking both prior to plowing under the crop and after. This establishes contact of the plowed furrow with the soil body and its moisture supply. In the chernozem zone this operation is more important than in the zones of laterization and podzolization, since the paucity of precipitation dictates closer watch on conservation of moisture.

The better system of handling a green manure crop in the chernozem zone, in the situation described, is to seed a mixture of a legume and grass. This combination, even though not new, has been stressed in recent years for the zone of chernozem in Russia and western Europe. The papers of Chizhevskii and Losinskii (1953) and Burov (1953) provide ample data to prove this point. The green manure crop should be deprived of nutrients, whereby root growth would be enhanced and top growth inhibited. Reducing the top growth to a minimum, less moisture is used by the green manure crop and the danger of producing the cushion referred to is eliminated. It is to be remembered that in the chernozem zone, even with relatively high spring rains, the surface soil dries faster than in the zone of podzolization, and every effort has to be made to conserve moisture. If, for any reason, a heavy green manure crop is produced, it should be removed and its fertilizing value, in terms of NPK plus some magnesium, should be added as mineral salts when plowed under.

In view of the paucity of information on the practices of green manuring in this zone, modifications of the expedients suggested in this paper are to be guided by local experiences and interpreted in the light of the specificity of the processes of soil formation as dictated by the zonality principle. In this manner it should be possible to adjust the steps in carrying out the green manuring operations favoring the positive effects and keeping down to a minimum the negative effects.

As we enter the areas of chernozem adjoining the zone of chestnut-brown and brown soils of the arid steppe, the moisture relationships effect precludes green manuring. Sod in the rotation is used for a year or two, with the top growth used for purposes other than plowing it under.

a. Burning the Straw in Grain Culture. In the areas where grain culture prevails, there is the problem of handling the standing straw after combining the grain. Whenever it is economical to remove the straw from the fields, the minor problem of returning to the soil the minerals carried away by the straw is similar to that of returning minerals carried away by the grain. The loss of minerals caused by the

removal of the crop is usually compensated by returning to the soil some animal manures and mineral fertilizers. Where removal of straw is not economical, the difficulties engendered by plowing it under re-introduce the practice of burning it. Because of space limitation an airing of the pros and cons of this practice has to be postponed. A few remarks will suffice at this juncture.

When we have accepted the view that one of the most important effects of green manuring is not the supply of organic matter but the mobilization and release of plant nutrients, the burning of straw may be evaluated in a more rational light. This controversial practice has in its favor two points: (1) very little loss of nutrients is the result; (2) the array of attendant disturbances are obviated. In addition the probability of nitrogen fixation should not be ruled out. This problem should be dealt with by a specialized team of soil microbiologists well trained in the genetic school of soil science, well grounded in the fundamental sciences, supported by a staff of biochemists, physicists, pedologists, and agronomists with similar backgrounds. The study should be made on a meridianal scale. With the modern tool of isotope techniques, a study of this kind offers an opportunity to uncover the elements of the specific process of soil formation that are responsible for the positive and negative effects of nitrogen fixation associated with the expedients of green manuring in the respective zonal soils.

In this connection one should ponder over the fact that by shredding and chopping up organic matter and incorporating it into the surface 2 to 3 inches of the soil, the effects of burning are simulated. The difficulty of this approach lies in the contradictions that arise from a slow or speedy rate of decomposition of the organic matter, as discussed earlier in this paper. This phase may become a part of the study suggested.

2. Soil Types under Irrigation

These soil types preclude the practice of green manuring unless an artificial supply of moisture is added. The geographic area of these soils includes the chestnut and brown, desert-semidesert climatogenic types of soil formation, and the climatogenetically subordinated or subdued hydrogenic saline types of soil formation, namely, the solonchak, solonetz, and solodi. These soils differ from the senior member of the pedocals, the chernozems, in a number of specific processes, of which the root system is singled out for the purpose of illustrating the manner in which green manuring may be effectively practiced.

The bulk of the root system in these soils is concentrated in the relatively shallow A horizon. Tap roots or heavy branched roots do

enter the B and even the C horizons. Records to this effect are to be found in investigations dealing with the problem of depth of penetration of roots. The shortage of moisture entering the A horizon in this geographic area is not the only limiting aspect of moisture supply to plants. The low moisture-holding capacity of the B horizon is probably just as much of a hindrance as the total short supply of precipitation. In the chernozem soils this horizon serves as a great reservoir of moisture. The low reservoir capacity of the soils under consideration is in large measure determined by the high content of carbonates of calcium in the B horizon and consequent low clay content. The relatively high silt content of these soils and consequent low clay content impose a low field capacity for moisture which restricts the development of an extensive root system. It is because of this condition that the structure of the soil in this area is not highly developed. Of course, the conditions described become more acute as we move from the chestnut-brown soils adjoining the chernozem towards the brown and gray semidesert types of soil formation.

With the application of irrigation water, the more prolonged periods of keeping up the optimum range of moisture for crop growth throughout the profile extend the feeding area for the root system and probably influence favorably the capillary rise of water (the dangers of salinization are a subject by itself and are assumed at this juncture not to be involved).

With the introduction of irrigation, green manuring may be utilized to fullest extent, aiming at the most desirable effects, the mobilization and supply of nutrients and a chance for improving the soil structure. In short, the positive effects of green manuring, as discussed for the pedalfers (zones of laterization and podzolization), may readily be attained. Conditions of the system of agriculture followed in any particular section of this area may call for some modifications of expedients suggested.

The climatic conditions of this area afford better chances of utilizing these effects. For one thing, the growing season is longer and with the moisture factor under control the chances for success in these areas are much greater.

With the changes in the rhizosphere induced by irrigation, the reactions associated with the processes of humification and mineralization of the organic matter supplied by the roots and stubble of the green manure crop (it is assumed that the top growth is not to be plowed under and wasted) may over a period of years introduce a number of changes in the profile. It is probable that the carbonate layer may be pushed deeper, the clay content increased, the A horizon deepened, and moisture-holding capacity increased. In prospect is the encouragement

of some of the desirable attributes of the chernozem type of soil formation. Although these are speculative ideas, they lend themselves to experimental verification and may be included in the scheme of the meridianal study suggested in Section IV, 1*a*.

Green manuring in the areas of the saline type of soil formation is practiced in a large measure for the purpose of increasing the buffer capacity of the soil, thereby mitigating the negative effects of the higher salt content usually present. To accomplish the high buffer effect, heavy top growth is looked for to be plowed under. Very few reports are available on green manuring problems connected with soil management practices on irrigated land in general and in particular with the problem of disturbances accompanying the practice of plowing under heavy top growth. Among the latest reports on this subject are the papers by Lukashev (1950), who deals with the buffer capacity of irrigated soils, and by Golubev (1952) on the decomposition of green manures in irrigated chestnut-brown soils. Actually, these reports are nothing more than results of empirical trials in the area under consideration.

It would seem that in order to attain the highest buffer capacity, the green manure crop should be plowed under at a time when the moisture content is low. Irrigation is to be withheld until the slow rate of decomposition has come to a standstill and desiccating reactions have fixed the organic complexes and have increased their resistance to decomposition. Shallow mixing of this highly buffered humified organic matter would enhance the result desired.

V. Concluding Remarks

Green manuring in the scheme of tilling the soil for bigger and better crops has been appreciated for a long time, especially by progressive farmers whose experiences have contributed a great deal to present the problems involved. The scientific agriculturists lagged behind in interpreting gains made and in explaining failures, thereby causing confusion and misunderstanding on the value of green manures. The literature on this subject, even to date, reflects helpless theoretical anchoring and poor comprehension of the mechanism involved in the functions of green manuring. Misleading and frustrating have been the attempts to duplicate results of one and the same practice in different parts of the world.

The underlying cause of the confusion prevailing and lack of progress in utilizing the potential benefits of green manuring practices lies in the inappreciation of the zonality principle operating in nature. It is shown that the pedologic approach, based on this principle, offers an opportunity to clear the air of misapprehensions and provides rational interpretations of the true nature of reactions set off by green

manuring in the respective zonal soil types. With a clear understanding of these reactions maximum benefits may be gained by following expedients tailored to fit the reciprocal reactions of the green manure effects and those involved in the broad fundamental and specific soil-forming processes.

The approach, stemming as it does from an application of the natural laws governing the origin, formation, and geographic distribution of the soil as a body in nature, is sound and offers a chance of coordinating the reciprocal reactions mentioned and of advancing the benefits of green manuring.

It should be clear that deductions made for the expedients suggested are based in some measure on experiments designed empirically for other purposes. This circumstance may call for some modifications of procedures and perhaps some experiments designed for that purpose.

Each zonal soil with its characteristic pedologic features has its own mode of reactions to one or the other procedure. While most of these reactions may be theoretically anticipated, some experiments to prove the theories and ideas are in order. To this end a meridianal type of experiment is suggested.

It is felt that we have not exploited the full potential of benefits that can be obtained from green manuring for better and bigger crops.

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Plant Introduction as a Federal Service to Agriculture

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CONTENTS

I. Preface

Long before the beginning of any systematic agriculture, prehistoric man practiced a kind of unorganized plant exploration. As a wandering fisher-hunter and food-gatherer he was forced to explore daily in order to satisfy the primary and ever-present urge of hunger. With the establishment of primitive agriculture came the first true introductions of plants—from the wild into man's garden plots. Although the culture of plants permitted a more sedentary existence, man did not entirely cease his wanderings. The pressures of civilizations made him also a colonizer. With him went his plants. The success of his plant introductions has been amazing and is typified by such important crops as wheat, potato, coffee, and rubber, the centers of production of all of which are now far removed from the native homeland of the parent species.

The history of plant introduction on this continent, as elsewhere, started with the wanderings of aborigines who brought in what we commonly think of as "native crops"—maize, pumpkin, squash, bean, and

the like—from tropical areas to the south. Not a single agronomic species and no truly major crop plant originated in land now included within the geographical borders of the United States. All except such indigenous plants as the sunflower, blueberry, pecan, and cranberry came from foreign lands. Even these indigenous plants required introduction from our fields or woods to our garden plots.

From domestic and foreign germ plasm, strains and varieties have been selected or bred to fit the needs of our environment. The need for plant introduction is a continual one. This is so because new diseases, such as internal cork of sweet potatoes and tristeza in citrus or new strains of old diseases, exemplified by the virulent 15b strain of wheat rust, are continually appearing. The disastrous havoc of such plant diseases alone makes it imperative that our agronomists be constantly supplied with possibly resistant materials for trial, and that reservoirs of basic plant material be maintained to supply the needs of our plant breeders.

In the early days, following the discovery of the Americas, colonists, adventurers, and explorers brought with them seeds and plants from the Old World. Plants from other parts of the New World were also brought in, the potato being an important example. These plants became established and spread in the rapidly developing colonies.

As settled community life followed the rough pioneering days in the colonies and homes followed homesteads, more and more attention was devoted to bringing over from the Old World the best of fruit trees, ornamental and flowering plants, shade trees, and food and fiber crops. Many important collections, the influence of which was far-reaching, were built up in these early years. At the same time there was tremendous interest on the part of the Old World gardeners in the new species and types of plants to be found in America. Extensive collecting activities were conducted and immense quantities of plant material were sent to Europe.

II. Federal Participation in Plant Introduction

With the organization of an independent government in the colonies, pressing problems of a political nature occupied the minds of officials almost exclusively in the early years. Individual officials recognized the importance of plant introduction, but governmental recognition was much slower. In 1827 President John Quincy Adams directed all American consuls to forward to Washington rare plants and seed for distribution. Twelve years later, in 1839, Congress passed its first appropriation for agriculture—a sum of $1,000—to be used primarily in collecting and distributing seed. This undertaking was then under the

direction of the Patent Office and marked the beginning of an ever-increasing group of activities which ultimately led to the organization of the Department of Agriculture as a separate agency of the Government in 1862.

Under the Department plant introduction continued to expand, and many valuable contributions to American agriculture were made. Of the earlier fruit introductions that have become of major importance, the Washington navel orange, introduced from Brazil about 1870, is an example. The oriental persimmon, *Diospyros kaki* L.f., was also introduced about this time. As the Department grew and the demands for the sustained introduction of useful plants increased, a separate unit was created in 1898 to centralize such activities for the Federal Government. This unit was originally known as the Office of Foreign Seed and Plant Introduction, later shortened to the Office of Foreign Plant Introduction. More recently it carried the name Division of Plant Exploration and Introduction of the Bureau of Plant Industry, Soils, and Agricultural Engineering. With the abolition of all bureaus in the Departmental reorganization of 1953, the name of this unit was simplified to Section of Plant Introduction. Despite name changes the functions of this unit have remained essentially the same down through the years.

The special duties of this Section are to secure by exploration, purchase, and exchange, new or otherwise valuable plants which give promise in themselves or in the hands of plant research workers of the various state and federal stations of making valuable contributions to our agriculture. In the years since 1898 there have been brought in over 220,000 plant introductions, inventoried under P. I. (Plant Introduction) numbers, as they are familiarly known to the workers who utilize these materials. Some of these introductions, such as the soybean and crested wheatgrass—new crops for this nation—have revolutionized the agriculture of large areas of the United States; others, like the little wild tomato of Peru, *Lycopersicon pimpinellifolium* (Jusl.) Mill., the disease resistance of which has been bred into a half dozen commercial tomato varieties, have played obscure though highly important roles known only to plant breeders.

III. The Section of Plant Introduction and Its Organization

The Section of Plant Introduction is conducted as one of several administrative units of the Horticultural Crops Research Branch of the Agricultural Research Service with headquarters at Beltsville, Maryland. Fundamentally, the purposes of the Section are two: the introduction into cultivation of new plant materials from all parts of the world, and the preliminary testing of this material for potential use in

the agriculture of the United States. Such research as is conducted within the scope of the Section's work is related directly to one or the other of these basic purposes. A headquarters staff of plant introduction specialists administers the over-all program of the Section, planning explorations, arranging for exchanges or purchases of material from abroad, receiving, recording, and assigning new introductions to quarantine propagation when necessary, trial, or experimentation.

An important present facet of the work of the Beltsville staff is to obtain plant materials in the United States needed by foreign research workers and to forward it to them for use in their investigations. The increase in United States Government missions aiding in technical assistance programs abroad has amplified this procurement work tremendously, with the result that the Section's headquarters now must be in a position to act as the clearing house for all requests for experimental lots of plant germ plasm originating from foreign sources. Insofar as is possible every effort is made to supply the requests of foreign research institutions. In this way, friendly cooperation is fostered and mutual assistance rendered, making it far easier for the Section to conduct its own procurement programs abroad.

The Section of Plant Introduction also maintains agricultural explorers in the foreign field; an Inspection House in downtown Washington, D. C. (in cooperation with the Plant Quarantine Branch of the Department), through which all Departmental plant materials entering or leaving the country are funneled; and isolated propagation facilities at Glenn Dale, Maryland, for introductions requiring quarantine. It administers four federal plant introduction gardens and has a cooperative part in the operations of five regional and interregional state-federal introduction stations at widely scattered locations to aid in the preliminary increase, testing, distribution, and maintenance of plant introductions.

1. Plant Introduction

a. Plant Procurement and Exploration. The bulk of the plant material introduced from foreign and domestic sources is obtained through correspondence, by exchange, purchase, or gift. A great part of it is obtained by deliberate intent, to be used in specific breeding programs or tested for use in the diversification of the agriculture of some region, but some also comes in unsolicited from travelers, foreign service workers, and friendly governments as international exchange.

Actual explorations are conducted when the plant materials needed cannot be obtained by other means, or when an intensive survey is necessary to obtain materials for important crop programs in specific

regions. Through explorations come the most valuable introductions, the wild relatives of our cultivated crops, the locally grown strains and varieties which may have genetic characters useful to the breeder, and occasionally plants which may be the basis of completely new crops for the United States. Exploration has been one of the most important activities of the Section. The list of plant hunters who have trodden the obscure corners of the world in the search of desired plants for the Section contains, among others, such well-known names as David Fairchild, Walter T. Swingle, S. A. Knapp, N. E. Hansen, E. A. Bessey, Frank N. Meyer, O. F. Cook, T. H. Kearney, H. V. Harlan, Joseph F. Rock, Wilson Popenoe, P. H. Dorsett, H. L. Westover, and Walter Koelz. The present generation is also contributing its share to the explorers' ranks. Since the termination of World War II about a dozen men have been in the foreign field; among them are Jack R. Harland, J. T. Baldwin, Jr., Donovan S. Correll, Howard Scott Gentry, and R. K. Godfrey.

The planning of explorations receives much time and attention from a considerable number of scientific workers and agricultural agencies. The guiding principle behind each exploration is the need for and importance of a specific crop or group of crops. Pressing needs sometimes develop suddenly, as in the recent ravages of the virulent new strain of rust 15b on the nation's chief wheat varieties. Breeders required all types of resistance as quickly as possible. Because of this need the Section immediately sent an explorer to Ethiopia, a known center of rust resistance and thus one of the most likely areas in which to find resistant stocks.

Internal cork, a new disease of sweet potatoes, has become such a threat to growers in the southern United States that breeders need possible resistant strains to use in its control. Almost as soon as this request had been received by the Section, a botanist and horticulturist teamed up in an exploration to the Greater Antilles, believed to be a center of dispersal of the sweet potato.

Most explorations do not develop on such short notice but arise from cooperative planning between workers at state and federal experiment stations, who bring together suggestions as to geographical areas to be explored and special crop groups to be collected, as well as to the order or priority in which explorations are to be made. The Section then undertakes the exploration work based on these recommendations (both in the foreign and the domestic field). Because of the importance of the Middle East and the area of southwestern Asia adjacent as one of the important centers of origin of a host of our domesticated plants, this region is being systematically explored at present. Since 1948 plant

hunters have traversed Turkey, Afghanistan, West Pakistan, and India, and it is planned that the adjacent countries will also be covered.

A primary reason why our plant breeders must obtain new stock from different parts of the world is that new varieties can be produced only if the right raw materials are at hand. The greatest natural resources of agricultural plant germ plasm are in the centers of origin of our domesticated crops. For example, West Pakistan, Afghanistan, Iran, Turkey, and neighboring parts of the U. S. S. R. are rich in cereals, legumes, forage plants, vegetables, and fruits. In such mountainous countries of still primitive agriculture hundreds of ancient crop types are still to be found in geographical isolation. No one can predict the value of such types in modern breeding programs, but we do know from past experience that it is just such seemingly useless plant introductions which have proved of outstanding merit in the improvement of our modern commercial crop plants. To many of these backward countries the borders of which encompass ancient centers of varietal wealth have gone in recent years American or United Nations agricultural missions. Besides supplying technological advice on agricultural problems these groups, in order to improve the local economy, have been introducing standardized crop varieties. Thus our own technology is contributing to the loss of varietal wealth from the ancient reservoirs of crop germ plasm. Our modern varieties are rapidly replacing the primitive native types. In the United States hybrid maize has caused the virtual disappearance of a wealth of open-pollinated types within a decade. When hybrid maize varieties become established in the New World center of origin for this crop, our agricultural economy had best beware, for we are already finding ourselves in the dilemma in which the primitive and technologically backward countries cannot afford to keep their great varietal resources and American agriculture cannot afford to let them be discarded. The urgency for sustained exploration is more than evident.

Besides agricultural exploration undertaken with regular appropriations of the Section there may also be other explorations supported by special funds which become available from time to time. A current example of such special work is one in which search is being made for possible plant sources of cortisone. To date eight explorers have cooperated in this endeavor in the field, and their foreign wanderings for such botanical items as *Strophanthus*, *Agave*, and *Dioscorea* have covered much of this hemisphere from Mexico to Chile and much of Africa from Liberia to the Cape of Good Hope.

The work of agricultural exploration may be carried out by regular scientists on the staff of the Section or more frequently by others (usu-

ally professional men attached to experiment stations, colleges, or universities) who are hired on a temporary loan basis by the Section. Agricultural science has become so compartmentalized that it is obviously impossible to maintain a large staff of explorer specialists who can cover all the different fields. In practice, therefore, the Section sends when available the best qualified men for the specific problem in hand. For general explorations an experienced field botanist is most desirable, for many requests for specific plant items require a knowledge of all plant families and especially the ability to recognize many unrelated species in the field. When funds permit, a botanist-agronomist team or a botanist-horticulturist team, such as that which in 1953 collected sweet potatoes, as well as many other miscellaneous items, in the Antilles is preferable. In this case the horticulturist was a sweet potato expert. In addition to possessing a good professional background, plant explorers must be in good physical condition, for most of the areas of exploration are in areas still considered primitive. Youth is therefore a premium prerequisite for any candidate for exploration.

b. Inspection House. Whatever its original source or manner of procurement by the Section, each plant immigrant (after passing through a port of entry) first visits the "Ellis Island" of the Agriculture Department, represented by the Inspection House located at 224 Twelfth Street, S. W., Washington, D. C. This address should be in the file of every worker either requesting plant material from cooperators abroad or wishing to send domestic material to foreign correspondents. Germ plasm (if successful in passing inspection at this location) has a far better chance of reaching its ultimate destination.

The Section of Plant Introduction has no regulatory functions nor does it issue permits for the entry of foreign plant material. These functions pertain to the Plant Quarantine Branch, U. S. Department of Agriculture, Washington, D. C., which issues such permits as a part of its responsibility for guarding our borders against the promiscuous entry of plant materials which may contain pests and diseases of potential harm to our agricultural crops.

The Inspection House in Washington is operated cooperatively by the Plant Quarantine Branch and the Section of Plant Introduction. It is partly because of this closely integrated operation that the Section is the only organization permitted to bring into the country all categories of plant material, even to introducing cultures of disease-producing organisms for study by pathologists, but only under regulations of the Secretary of Agriculture as administered and supervised by quarantine officials.

At the Inspection House, personnel of the Section and inspectors

of the Plant Quarantine Branch, working in close cooperation, open the packages containing plant introductions, give the individual collections in the shipment Quarantine (P. Q.) and Plant Introduction (P. I.) numbers for the purpose of inventory, and inspect the material for diseases and pests. Depending on the kind of material and its condition on arrival, the inspectors may order it to be grown in quarantine, give it some fumigation treatment, or order it destroyed if it is too badly infected. If quarantine is not necessary an order is made to the Inspection House by the Beltsville staff to forward the material to the investigator or organization originally requesting its procurement, or with whom the Section may have cooperative arrangements for testing its value, as in the case of the regional cooperative state-federal plant introduction stations. If the introduction is of a kind that is of no immediate interest to any investigator or agency other than those on the Section staff, it is ordered to one of the four federal introduction gardens operated by the Section for propagation and testing.

Besides the plant introduction or accession number mentioned other data must be added to the Section's information file which is brought together for each plant immigrant. The data vary with the original collector, but most explorers include the technical and vernacular names when known, exact locality data, and pertinent descriptive, ecological, or economic notes which may be of interest to those who may wish to utilize the plant introduction. These notes are too voluminous to be included with each introduction as it passes into test programs, but workers should be aware that they are available upon request to the Section. Although there may be a delay of several years from the date of introduction, most of this information eventually appears in one of the printed plant inventories which have been issued continuously since the formal establishment of a federal unit for plant introduction in 1898. Thus there is on permanent file in libraries throughout the country, as well as in leading agricultural libraries abroad, the only permanent record of all plant introductions made by the Department of Agriculture. It should be emphasized that this is only a chronological record of the plant introductions which have been inventoried by the Section at the Inspection House. The inventory is not a list of plants available for distribution, for, of course, some may be destroyed as a quarantine precaution; others are requested by individual workers for their own use; and many fail to grow. Introductions which do survive and become available for distribution are listed much later as available on the seed or plant lists issued by the introduction gardens and stations.

Accurate descriptions and identifications of incoming material are

essential parts of the necessary records kept in connection with introduced plants. Often only seeds are received and identification depends upon them. Therefore, at the time the Section was organized a collection of seeds was started, and a sample of each introduction has usually been kept for comparison purposes so that there are now about 55,000 samples, varying in size from those almost microscopic to the giant double coconut. A botanist who has specialized in the identification of plants by means of seed is in charge of this collection, which in quality and size is one of the finest extant. Other botanists on the staff at Beltsville help determine the correct classification of introduced plants either from herbarium specimens made by the explorers or from plants propagated in this country from the original introductions. Staff botanists also investigate the areas of geographic origin of our cultivated plants to determine closely related species and varieties which may be of value in crop improvement programs. Monographic treatments are prepared for economic plant groups in need of clarification, and floristic surveys of botanically little-known regions are made as needed. As an aid to these botanical investigators the Section maintains, in addition to the seed collection, a reference herbarium of authentically named specimens and files of vernacular plant names used in different parts of the world.

Photographs are also a most important part of plant records. During the long period in which plant introduction has been carried on, photographs have been taken in the foreign countries where the plants were procured and also in this country where they were tested. This has resulted in a collection of thousands of photographs illustrating a wide range of plant life in all parts of the world.

c. Quarantine. Federal quarantine regulations, as stated in foregoing paragraphs, are administered by the Plant Quarantine Branch, Agricultural Research Service, Washington, D. C., from which may be obtained current information on the quarantine status of any plant material in which a research worker is interested. The most recent statement dealing with most quarantine material is contained in Nursery Stock, Plant and Seed Quarantine No. 37, effective December 5, 1950. The various states have their own quarantines which are independent of those described here.

In general, plant introductions subject to quarantine are those imported as vegetative or clonal propagations. Plants introduced as seed are seldom prohibited by quarantine procedures, but even here there are exceptions.

Quarantinable material is of two categories: (1) that class of plant

material that may be introduced and grown under specified conditions of isolation and periodic inspection until certified as free of injurious insects and diseases (post-entry quarantine) and (2) that material entirely prohibited except when allowed to enter for research purposes by the U. S. Department of Agriculture.

Plants involved in post-entry quarantine may be sent directly to a state location or in some instances the procedure may be modified to consist of one season's observation at the Section's plant introduction garden at Glenn Dale, Maryland, and another at the state locations.

FIG. 1. Citrus germ plasm undergoing quarantine in the compartmental quarantine houses, Glenn Dale, Maryland.

The quarantine usually covers a period of two growing seasons but may be extended under some circumstances. A great deal of post-entry quarantine material is handled at Glenn Dale in an isolated nursery, where it can be kept under observation by inspectors of the Plant Quarantine Branch. This type of quarantine entails the least work of all quarantine procedures.

The entry into the United States of clonal material of many species of plants is prohibited by law. Examples include grasses, citrus, grapes, white and sweet potatoes. Because it operates special quarantine greenhouse facilities the Section of Plant Introduction is excepted from this

restriction and can bring in restricted items for experimental and scientific purposes. For this reason the Section should be approached by workers desiring to bring in materials of a prohibited nature.

Plants to be quarantined are grown in specially constructed quarantine houses at Glenn Dale, Maryland, and kept until fresh growth is secured for propagation, after which the original plant is destroyed. Certain of the quarantine houses have been specially designed with fine screening all around including the ventilators, and with special oil moats inside and out and on the bench legs as protection against insect vectors of viruses and other pathogens reaching the plants. Furthermore these quarantine greenhouses are divided into isolated sections, each having a separate entrance from an enclosed corridor areaway.

The procedure in handling clonal introductions of citrus will give an idea of how quarantine works in the compartmented houses. Introduced citrus plants are potted in sterilized soil and placed in specially designed cages for a period of observation. Each case is a miniature quarantine unit in itself and is large enough to hold six to eight large plants, so that clones from each country or area can be held separately during the first stage of detention. Stock plants are grown in pots on benches in three of the sectional compartments, and on these a progressive series of budding can be done. As propagation from citrus plants in the cages is approved, buds from the new growth are set on stock plants in the adjoining section.

If the citrus variety is introduced in the form of budwood, it is propagated on stocks in the section containing the cages. After release, buds from the new growth are also worked on stocks in the adjoining section. The process is repeated in the second section, buds from the new growth, when released, being set on stock in the third section. This is the last budding while the material is subject to quarantine. If the plants of this last propagation are found free of diseases, they are moved to a nonquarantine area and as an added precaution are held under observation for an additional period of approximately six months. At the end of this period they are inspected and, if no disease symptoms are evident, shipped out to interested research workers.

Quarantine procedures at their best are not perfect, and they should be and are subject to revision as our knowledge of the insect and disease pests of plants increases. In recent years more and more information has accumulated on serious virus diseases detection of which under quarantine procedures is often difficult. It is expected that indexing techniques will have to be resorted to during quarantine for plants subject to such diseases. This is but an example of how quarantine procedures periodically must be revised.

2. Propagation, Testing, and Distribution of Plant Introductions

Once a plant introduction has been received by the Section, inspected, declared free from pests and diseases, identified, numbered, and recorded, it is ready for the next steps—propagation, testing, and distribution. The original introduction, whether in form of seed or clonal material, is usually limited in quantity and so has to be increased before it can receive wider distribution and testing. Preliminary testing and increase of stocks is usually done at field stations scattered throughout the United States, where a first idea is gained as to the potential usefulness of a plant immigrant to the agriculture of the United States.

The Section of Plant Introduction operates four federal plant introduction gardens. It also cooperates in the administration of five state-federal regional plant introduction stations. Whether an introduction is ordered to be sent to one of the federal or to one of the state-federal locations depends upon the nature and type of plant. The great bulk of plant introductions represent germ plasm of established crops which is to be used in specific breeding programs. Much of this material falls in the category of field or vegetable crops and so is funneled to the state-federal cooperative stations which are specially set up to handle them. To the federal plant introduction gardens go plants to be quarantined, woody species which cannot be handled as annual crops, certain types of ornamentals, and all little-known plants concerning the potentialities of which as new crops little is known. The only important exceptions are certain important agronomic crops including the small-grain cereals, cotton, and sugar cane. Facilities and personnel are not available to the Section for the large-scale quarantine propagation required by these crops, and, since the work can be more satisfactorily carried out by specialists, all plant introductions of these are turned over to the investigators in the several crops units of the Department of Agriculture for growing under quarantine, testing, and distribution to the states.

a. Federal Plant Introduction Gardens

Gardens were early recognized as essential to the success of a regular program of plant introduction and establishment. Historically they go back to the formal initiation of the unit back in 1898. In that year the first propagation garden was set up at Miami, Florida, on a little 6-acre tract on Brickell Avenue. A few years later, in 1904, enthusiastic citizens of Chico, California, became so interested in having their town chosen as a second site for a similar introduction garden that they purchased 80 acres of land and turned it over to the Federal Government for this purpose. An urgent need for a location near the Inspection

House at Washington, D. C., finally resulted in the establishment in 1919 of the garden at nearby Glenn Dale, Maryland, where immediate care could be given to plant material weakened by long transit from abroad. The last of the four federal locations, the Barbour Lathrop Plant Introduction Garden, Savannah, Georgia, was also established in 1919 as a gift of its namesake, who hoped to preserve for posterity a grove of the giant timber bamboo that was growing on the property.

Because of the necessity for propagating rapidly a wide series of plant material the growth requirements and life histories of which are often little known, the Section undertakes research on propagation

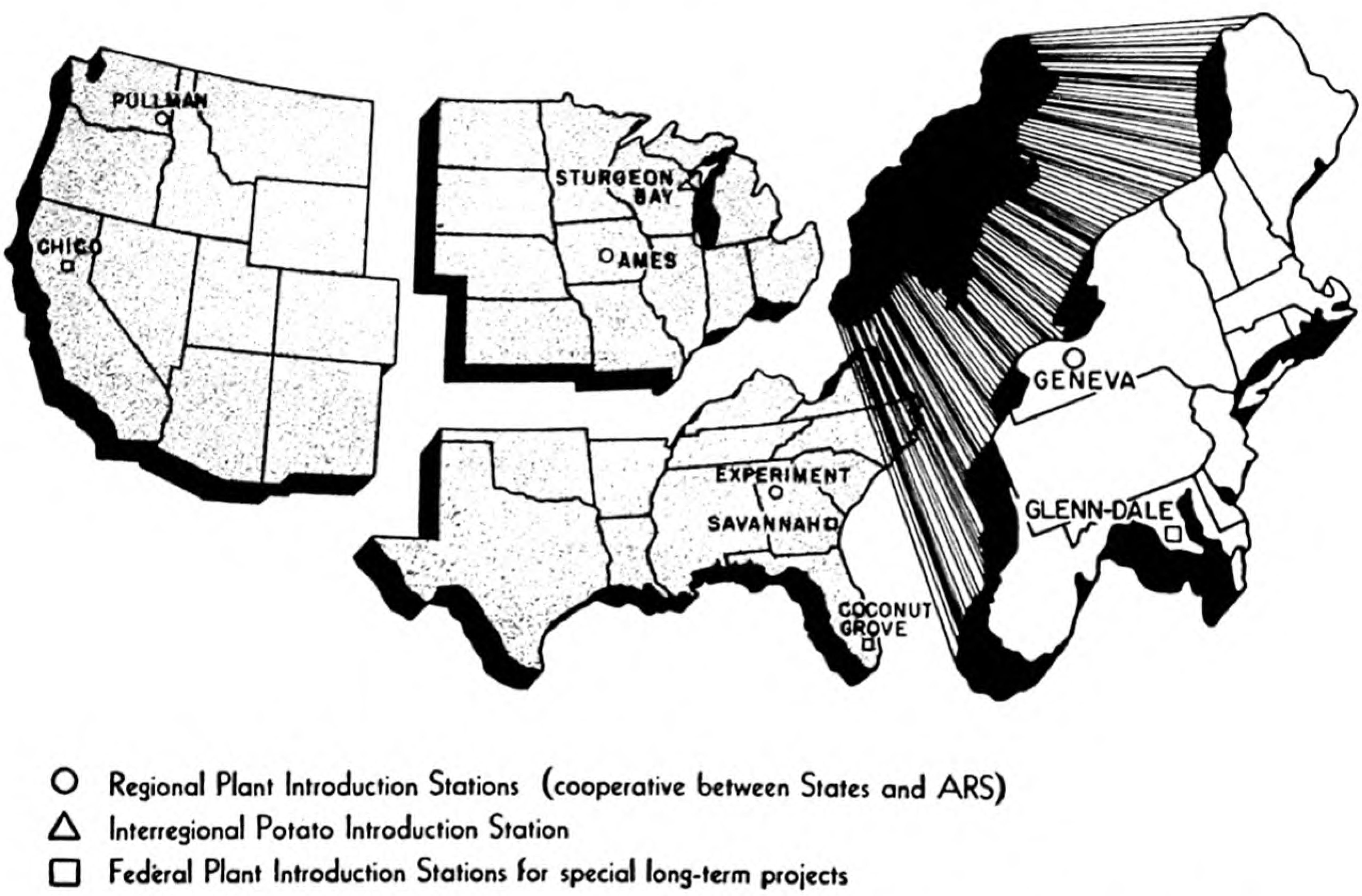

FIG. 2. The primary locations handling plant introductions in the United States.

methods at its federal introduction gardens. The adaptability of various types of media for the germination of seed, the use of various wavelengths of light for seedling growth and for the rooting of cuttings, and the efficacy of growth hormones and various techniques for the growing of plants are being investigated or have been investigated. Since the introduction gardens have handled thousands of shipments of living plants they have also developed special techniques, such as the use of polyethylene wrapping and sphagnum rooting medium, to insure that plants arrive safely at their ultimate destinations.

Some types of plants sent to the introduction gardens receive much more exhaustive tests than others. These have to do with material with which the Section hopes to establish entirely new crops for the United

States or, if the material is not new, to establish a new method of utilization for an existing crop. Often the bringing together of species and varieties and the study of their taxonomy and life histories, growth habits, adaptability, and economic utilization require investigations running into many years before selected introductions can be recommended to growers. Examples of now well-established specialty plants which have "graduated" from the Section's program include the Glenn Dale hybrid azaleas, avocado (*Persea americana* Mill.), date palm (*Phoenix dactylifera* L.), tung (*Aleurites fordii* Hemsl.), and dasheen (*Colocasia esculenta* (L.) Schott.); among plants still "matriculating" can be mentioned timber bamboo (*Phyllostachys* spp.), pistachio (*Pistacia vera* L.), and cortisone-yielding dioscoreas (*Dioscorea* spp.).

In the course of making exhaustive tests on certain categories of material large collections are built up and held for long periods. Although these collections change during the course of years, at any one time each of the federal introduction gardens may have several thousand introductions held in various stages of test. The introduction gardens therefore constitute important reservoirs or banks for plant germ plasm (Fig. 2).

i. *The Glenn Dale, Maryland, Plant Introduction Garden*

This is the most highly developed of the four federally operated gardens, serving as it does the nearby Inspection House in Washington and acting as the important center of all special quarantine activities undertaken by the Section. Although the garden totals only 70 acres (nearly all of which is under cultivation), it maintains some 6000 introductions under observation or test or in process of propagation for distribution. The most important series of introductions now undergoing preliminary evaluation are in the deciduous fruit category, with ornamentals next in importance. Ample greenhouse units and fine facilities for propagation of all types of plants have meant that the Glenn Dale Introduction Garden has been the one generally used for extensive jobs of propagation not only of specialty items for the United States but also for foreign aid programs of the Government as well (Fig. 3). Thus during World War II some four million seedling cinchona trees (quinine) were grown at Glenn Dale and distributed to Latin America. At present large series of coffees, the important spice, black pepper, and potentially valuable dioscoreas (cortisone) are being propagated extensively at this location. In 1952 a new seed storage unit was completed. In the special environment of its storage chambers, held at 33° F. and 30° relative humidity, are being kept a host of introductions in the form of seed the vitality of which, if held under normal storage, would soon be lost.

FIG. 3. Propagation increase of a cortisone-yielding species of *Dioscorea*, a potential new crop for the United States. Plant Introduction Garden, Glenn Dale, Maryland.

ii. *The Barbour Lathrop Plant Introduction Garden*

Located some 12 miles south of Savannah, Georgia, on U. S. Highway No. 17 is the smallest (50 acres) of the federal introduction gardens. Here is held a miscellany of ornamentals as well as plants of a so-called specialty-crop nature. Among the most important are outstanding hollies, edible aroids, cortisone-yielding dioscoreas, disease-resistant Chinese chestnuts, and the quite distinct Chinese water chestnut, or *matai*.

Above all this garden is noted for its germ plasm collection of hardy oriental bamboos, suitable to warm temperate areas in the United States. Utilitarian bamboos of the type to be seen at Savannah have been grown and used extensively for centuries by the peoples of China and Japan. It is believed that eventually many domestic uses will be found for bamboos if grown on southern farms. Perhaps the greatest potential of bamboo lies in industry, where it may serve among other things as an important new source of paper pulp. To investigate some of the industrial possibilities the Section has been supporting several lines of research on bamboo under contract, utilizing the plantings at Savannah as sources of test materials.

iii. *The Coconut Grove, Florida, Plant Introduction Garden*

Although Miami can boast of having the first federal plant introduction garden, the present one, some 13 miles south of Miami near Coconut Grove, is actually the third introduction garden in the general area. The little original Brickell Avenue plot soon outgrew its bounds and was supplanted by a tract at Buena Vista, north of Miami. The present garden occupies what was in World War I an Army aviation base, Chapman Field, later turned over to the Department of Agriculture in 1923. The garden has expanded since that date and now occupies some 197 acres, a third of which is still undeveloped. Here is a relatively frost-free testing ground for many tropical and subtropical introductions of interest to workers in peninsular Florida, the warmer parts of the Gulf Coast, southern California, Puerto Rico, the Virgin Islands and Hawaii.

Situated on rocky limestone soils Coconut Grove is not fitted for testing agronomic crops and so is almost exclusively used for woody species. About 7000 introductions held under observation and test include tung, coconuts and other palms, insecticide plants, mangos, lychees, papayas, as well as many other less known subtropical fruits. From the garden germ plasm collection have come budstocks of disease-free and high-yielding Hevea rubber trees now found in new plantations strategically located throughout the American tropics. A collection of world coffee varieties is currently being brought together to ensure coffee-producing countries of disease-free breeding lines should serious Old World coffee diseases gain entrance to the Americas. The last two are examples of plants of economic importance which, although of no interest to the U. S. farmer as domestic crops, are yet of extreme interest to American citizens, the world's greatest consumers of natural rubber products and beverage coffee.

Coconut Grove is especially rich in woody ornamentals, and the value of this introduction garden to subtropical horticulture is immediately apparent to the visitor to southern Florida, where the great majority of ornamental plants grown, whether as street trees or in gardens, can trace their parentage to immigrants originally tested by the Section at the garden.

iv. *The Chico, California, Plant Introduction Garden*

At Chico, in the irrigated Sacramento Valley of northern California, is located a fourth plant introduction garden of 210 acres in the center of one of the nation's leading drupaceous fruit and nut areas. Although formerly considerable emphasis was placed at Chico on ornamentals, the garden has always been and still is primarily a center for the evalua-

tion and increase of stone fruit and nut crop introductions. In the present collection are more than 1100 clones and varieties (as well as 3000 stone fruit seedlings), of which some 250 are cherries, 195 apricots, 450 peaches, 70 nectarines, and 200 plums. Also in the germ plasm collection at Chico are 250 to 300 miscellaneous woody (deciduous and evergreen) ornamental and specialty crop accessions, named pistachio nut varieties plus 750 seedlings and 9 *Pistacia* species, 200 English, or Persian, walnut (*Juglans regia* L.) seedlings, oriental chestnuts (*Castanea* spp.), plus miscellaneous fruits such as the Chinese gooseberry (*Actinidia chinensis* Planch.), Chinese date or jujube (*Zizyphus jujuba* Mill.), olive, pear, Japanese persimmon, and pomegranate (*Punica granatum* L.). Evaluation of any fruit or nut about which little is known consists of year-by-year recording of tree characters such as time of bloom, foliation, bloom hardiness, disease and insect resistance, and yield, and such fruit characters as size, color, quality, maturity. Though only a few may measure up to varieties grown in the United States, there are always outstanding characters of interest to the fruit breeder, who may utilize them in the development of still better commercial varieties.

b. State-Federal Cooperative Plant Introduction Stations

It has been mentioned earlier that, since the great bulk of plant introductions handled by the Section involves germ plasm (usually in seed form) of well-known crop plants, this material is turned over to state-federal cooperative stations rather than to the federal plant introduction gardens, which lack facilities and personnel to handle such work. Prior to 1946 most introductions of this type were farmed out to various crop experts in the Department, but for one reason or another this method of handling introductions was never completely satisfactory.

Under the Research and Marketing Act of 1946, funds became available for the first time to establish a truly national cooperative program for the introduction and testing of plant material for crop and industrial uses and for the preservation of valuable genetic stocks. In this cooperative effort the Section of Plant Introduction is held responsible for all exploration and introduction, while to the states and other cooperating agencies falls the job of evaluating introductions that are made in this program. Thus an opportunity is afforded to coordinate the introduction and evaluation of new plant material on a much broader and more thorough basis than has been possible before: broader because of the fact every state (as well as Puerto Rico, Hawaii, and Alaska) through its own experiment station can enter into the test program and more thorough because of reporting procedures required as a prerequisite to receiving introductions for test. As a result of this Act both the Section of

Plant Introduction and the states receive funds annually, in one case to conduct plant exploration and in the other to coordinate the testing and maintenance of plant introductions resulting therefrom throughout the nation.

Up until 1946 money for plant exploration had never been a regular part of the Section's budget but was dependent upon special legislation. Because of lack of funds for exploration a number of the early foreign expeditions of the Section were made possible only through the generous aid of benefactors such as Barbour Lathrop and Allison Armour. At present proposals for exploration may now be brought forward annually through official channels with good assurance of support. Whenever possible such exploration is proposed after consultation with the states and federal agencies cooperating, and active participation in the actual exploration of cooperators is invited.

Under Title I, Section 9b3, of the Research and Marketing Act, funds are made available to regional associations of states for the preliminary testing of introduced plant material, for cataloguing genetic stocks already available, and for preserving whatever basic germ plasm is deemed necessary to supply plant-breeding programs now and in the future. For operational convenience in coordinating this national cooperative program the United States has been divided into four regions, Northeastern, Southern, North Central, and Western, each with a regional project. A single interregional project has also been set up to handle white potatoes. The manner in which the cooperation develops for this national project, either regionally or interregionally, is decided by the states themselves through their agricultural experiment stations in consultation with the Agricultural Research Service of the United States Department of Agriculture as represented by the Section of Plant Introduction.

In each region there has been established a primary introduction station, with a regional coordinator in charge to supervise its activities. These regional introduction stations are located at Geneva, New York; Experiment, Georgia; Ames, Iowa; and Pullman, Washington; each is located at one of the principal state experiment station locations, where are to be found the necessary physical facilities including land for conducting regional operations. Plant introductions to be tested under this program go directly from the Inspection House to the coordinator at one or more of the regional stations.

Because of their geographical locations certain regions obviously are better fitted to handle at least the preliminary increase and testing of specific crop items. For example, peanuts, sesame, castor beans, and most tropical species (for Puerto Rico) go to the South; safflower is sent

to the West; maize is directed to the North Central Station (Fig. 4); and such items as timothy and eggplant go to the Northeast. Of course all introductions are eventually available to all regions interested, with the result that there is a free exchange of materials between regions through their coordinators. Cotton, sugar cane, and small grain cereals are items mentioned earlier as not being evaluated through this cooperative program. There is an additional item, the white potato, introductions of which are tested cooperatively through the special interregional cooperative project with headquarters at the Wisconsin Branch Experiment Station at Sturgeon Bay.

FIG. 4. Plant introductions (vine crops) undergoing initial increase and evaluation at the Regional Plant Introduction Station, Ames, Iowa.

Plant introduction material submitted by the Section to the regional stations is given sufficient preliminary evaluation so that interested state stations may be in a position to determine whether such materials may have potential value in their research programs. Involved also is the matter of multiplication of the accessions so as to enable as wide distribution of seed or plant lots as may be required. The greater proportion of plant material received at any primary introduction station is grown at the station, though in a number of cases workers interested in specific crops may take on the work normally done by the coordinator in return for having a "first look" at the introductions in which they are interested. Such arrangements are made by the individual worker through the regional coordinator in his own region. At the end of each year detailed seed or plant lists are brought together by each coordinator

for distribution to all state experiment stations, and these indicate the materials which are available through the regional primary stations.

All regional coordinators make regular visits to all state or other research stations in their territory. In this way they not only become aware of the specific needs of every worker but also gather the essential information as to which specific plant introductions are proving of value. A knowledge of such highly promising introductions and of how they are being used is not only of interest to agricultural workers in general but is also valuable information needed to obtain continued support for the whole program of plant introduction.

With the accumulation of plant introduction materials at the primary stations, each location is becoming more and more like a bank for holding valuable plant germ plasm. Much of this represents germ plasm of annual crops and so can be held in ordinary seed storage. That which is in regular demand, like a checking account, goes into the regional introduction station's own storage room. That which is potentially but not immediately important, like a savings account, may be temporarily stored in the rather limited facilities operated by the Section at Glenn Dale, Maryland. There is already a need for a national seed storage facility large enough to maintain permanently all valuable agricultural germ plasm as seed. Such a federally constructed and operated facility, proposed in recent years and backed by many scientific and commercial groups, still awaits favorable consideration by Congress.

The National Cooperative Program has now been in operation for six years. Under this program some ten foreign explorations have been made, all at the request of workers in the cooperating states. There is always a considerable but unavoidable delay between the time that plant material is procured abroad and tested and the time it becomes available for use in breeding or other programs. Despite this, cooperatively prepared publications are already beginning to appear reporting on certain types of evaluation which have been made under these programs. A specific example of this, sponsored by the North Central Region, is the bulletin reporting on the testing of a large series of tomato introductions for resistance to a number of well-known diseases. In this case a well-planned screening program was developed by plant pathologists throughout the country under the technical leadership of a state worker and ably assisted by one of the regional coordinators.

A similar type of cooperative screening is at present developing with sweet potato accessions received as a result of the exploration for this crop plant in the Antilles in 1953. In this case a federal crop worker rather than a state man is lending technical leadership but is being ably

supported by sweet potato men at state locations throughout the South. It is anticipated that more and more work of this type will be initiated and formally reported upon in publications.

IV. Benefits Resulting from Plant Introduction in the United States

Space does not permit the lengthy statement that would be required to mention even a major portion of all the valuable introductions that have become established in the United States. What follows is a summary of some of the more important introductions made by the Department.

The hard red winter wheats, with some 27,000,000 acres grown annually in this country, have all been derived from plant introductions. The varieties KHARKOV, KUBANKA, BAART, FEDERATION, PENTAD, WHITE FEDERATION, ONAS, GALGALOS, HARD FEDERATION, and KAHLA, the germ plasm of which was all introduced by the Department, are among leading varieties planted in many of the important wheat-growing regions. Among barleys, TREBI from Turkey and CLUB MARIOUT from Egypt are widely grown in the West, where rainfall is low. Our rice industry is based almost wholly on plant introductions grown on approximately a million acres and representing an annual value of $30,000,000; the same may be said in regard to other cereals such as oats, rye, and sorghum.

Forage crops also have been introduced in large numbers by the Department. The continuing demand for legumes and grasses is indicated by the fact that the last three explorations undertaken by the Section of Plant Introduction had as their primary purpose the collection of forage materials. Outstanding among forage grasses is crested wheatgrass (*Agropyron cristatum* (L.) Gaertn.), introduced from Siberia in 1898 and today having an annual farm value of $4,000,000. Many other now familiar grass immigrants are introductions, including centipede (*Eremochloa ophiuroides* (Munro) Hack.), Dallis (*Paspalum dilatatum* Poir.), Bahia (*Paspalum notatum* Flügge), Napier (*Pennisetum purpureum* Schumach.), and Rhodes (*Chloris gayana* Kunth) grasses. Their importance extends even to our lawns with the familiar common Bermuda grass (*Cynodon dactylon* (L.) Pers.) as well as those newer luminaries, Meyer Zoysia (*Zoysia japonica* Steud.) and African Bermudas (*Cynodon transvaalensis* Burtt Davy and *C. magennisii* Hurcombe).

Twenty-five years ago most of the soybean types (*Glycine max* (L.) Merr.) now grown in our country were collected in Asia by two of our plant explorers. Their two-year trip cost American taxpayers

about $50,000. The new industry they helped to found in this country is now worth more than a billion dollars a year. Taxes paid by producers of this crop alone have repaid many times the total cost of all plant introduction work since its formal inception in 1898. But soybeans are not the whole story. There are the alfalfas (*Medicago sativa* L.)—LADAK from India, Hairy Peruvian, and Creeping alfalfa from Turkey; all the clovers (*Trifolium* spp.), some dozen or more; kudzu (*Pueraria lobata* (Willd.) Ohwi); cowpeas (*Vigna sinensis* (L.) Savi); velvet beans (*Stizolobium deeringianum* Bort); crotalarias; vetches (*Vicia* spp.); and lespedeza. All our Korean lespedeza (*Lespedeza stipulacea* Maxim.) came from a handful of seed collected in 1919 by a plant explorer in Korea. That handful of seed has mushroomed into a $120,000,000 a year crop.

From the standpoint of cotton the most outstanding find of plant exploration was ACALA, the germ plasm of which has contributed to a series of superior, drought-resistant, big-boll cottons with an excellent, quality staple. Found over 30 years ago in southern Mexico as a dooryard plant in a hamlet from which it derives its name, ACALA cotton, in one or more of its selections, has subsequently become the most important cotton in the American Southwest. California growers alone pocket millions of dollars annually from this fabulous plant.

Horticulturists have long recognized the value of plant introductions and down through the years have been supplied with a rich heritage of plant germ plasm from abroad. Scores of varieties of beans, cabbages, carrots, lettuce, onions, peas, peppers, pumpkins and squashes, radishes, maize, and the like represent either direct plant introductions or first-generation selections. In these days of constant warfare against disease, present-day vegetable breeders are looking more and more to related wild species for use as parental material in vegetable improvement programs. The so-called Irish potato, wholly American in origin, is in itself a good example. Since 1932, 56 new potato varieties have been released in this country by breeders, and all but one can boast of foreign introductions in their pedigrees. What is more, selections of the wild potato species of Mexico and South America are showing up as a source of valuable genes. For example, *Solanum acaule* Bitt. selections, immune from X virus, have demonstrated that they can withstand temperatures down to 23° F.; *S. antipovichii* Buk. and *S. chacoense* Bitt. are immune from Y virus; and many introductions of *S. demissum* Lindl. carry late blight resistance. The same thing can be said of the tomato, wild cousin species of which from Peru have supplied resistant factors for such serious troubles as fusarium wilt and root-knot nematode.

In the field of tree crops results do not appear so soon because of

the slow growth of such plants. Yet even here examples of the contribution of the federal plant introduction program are legion. The Washington navel orange, introduced from Bahia, Brazil, is the basis of one of California's important agricultural industries. Among other fruits introduced mention must be made of the avocado, date, lychee, Quetta nectarine, Meyer lemon, Geneva apricot, Shalil and Yunnan peaches, and Methley plum. To this galaxy of trees should be added such items as the Chinese hairy chestnut (*Castanea mollissima* Blume), pistachio, and tung.

Of secondary importance in our agriculture, ornamental plants have always been overshadowed by their more important economic cousins in the program of plant introduction. Those that are woody also require long-term evaluation, as demonstrated by the fact that only in 1953 could a report be issued recommending for the northern Great Plains a series of several dozen hardy trees and shrubs collected some 40 years earlier by our explorers in northern China and Japan. That explorers have not entirely overlooked ornamentals has already been shown in the galaxy of showy tropical and subtropical woody plants which have emanated from the plant introduction garden at Coconut Grove to enrich the gardens of Florida and California. But there are others too: the famed Japanese cherries of Washington, D. C.; the Chinese elm (*Ulmus parvifolia* Jacq.); *Rosa xanthina* Lindl., which has been a principal gene source of hardiness and color in our modern yellow tea rose; *Ilex cornuta* Lindl., the Chinese holly, and its striking compact horticultural variety *rotunda*. Most recent contribution of the Section in the field of ornamentals is the fine series of Glenn Dale hybrid azaleas, the result of a breeding program in which were incorporated the genes of a number of plant introductions.

The illustrations given represent but a few of the host of successful introductions that have been made since 1898, when the plant introduction activities of the Department of Agriculture were formally organized. They indicate how indispensable is sustained plant introduction work to the dynamic agricultural economy of our nation.

The Enigma of Soil Nitrogen Balance Sheets

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CONTENTS

I. Introduction

During the past fifty or more years, many attempts have been made to draw up nitrogen balance sheets for both cropped and uncropped

soils. In general, these attempts have met with only mediocre success because quantitative data are usually not available for some of the items that enter into the calculations.

On the side of income, accurate values for additions in the forms of rainfall, irrigation water, seeds, fertilizers, and manures are usually available. However, if legumes are grown, there are difficulties. The quantity of nitrogen supplied from the air by rhizobia is not likely to be known accurately under field conditions but can, of course, be determined under special controlled conditions. Or the experimenter may avoid the problem by growing only nonlegumes. With regard to nonsymbiotic fixation, little is known about the quantities supplied under field conditions because they are commonly too small to be measured. Furthermore, any gains may be more than offset by unaccounted-for losses.

On the expenditure side of the balance sheet, accurate values for the nitrogen removed in harvested crops and in animals are commonly available. As for wind and water erosion, these are usually of only minor importance in carefully planned field studies. Leaching, however, presents a major problem. Seldom is it known what values to assign to this source of loss, and there seems to be a wide divergence of opinion among agronomists as to whether such losses are likely to be large or small.

After the balance sheet has been drawn up, income and outgo seldom balance, even though account has been made of all known soil nitrogen gains and losses. Usually all of the nitrogen that went into the system has not been recovered. It is assumed that some of it has volatilized. Is this true, and, if so, how is it lost and in what quantity? Only on rare occasions does income exceed outgo, if all of the nitrogen added by legumes is excluded. This failure of nitrogen balance sheets to balance constitutes the enigma of this discussion. In a broad sense, all items that enter into the nitrogen balance sheet are involved; in other words, there are several enigmas. The present discussion will, however, deal primarily with losses by leaching and volatilization, and with gains of soil nitrogen from the air through channels other than legumes. Such a discussion of nitrogen balance sheets should help to explain why recoveries of nitrogen in the crop are often only 50 per cent of that added as fertilizer.

II. Nitrogen Balance Sheet for the Cropped Soils of the United States

When the subject of nitrogen balance sheets is mentioned, the one published at New Jersey by Lipman and Conybeare (1936) imme-

diately comes to mind. In this study a major attempt was made to account for the income and outgo of soil nitrogen in the United States. A mass of data was assembled and studied, but they emphasized that in many cases quantitative information was inadequate for arriving at accurate values for the quantities of nitrogen gained and lost through the various channels. Their nitrogen balance sheet for cropped soils is shown in Table I.

TABLE I

Nitrogen Balance Sheet for the Harvested Crop Area of the United States, 1930

	Pounds of nitrogen per acre per year
Additions:	
Rain and irrigation	4.7
Seeds	1.0
Fertilizers	1.7
Manures	5.2
Symbiotic nitrogen fixation	9.2
Nonsymbiotic nitrogen fixation	6.0
	27.8
Losses:	
Harvested crops	25.1
Erosion	24.2
Leaching	23.0
	72.3
Net annual loss	44.5

It will be observed that no value is given in the table for nitrogen losses by volatilization. The net annual loss of nitrogen, therefore, may have been even greater than the value of 44.5 shown.

If Table I were to be revised to correspond to conditions in 1950, the most striking change in nitrogen additions would be an increase in the use of fertilizer nitrogen from 1.7 to about 6.7 pounds per acre annually. The value for addition of nitrogen as manure would be increased only slightly from 5.2 to about 5.7 pounds. The symbiotic nitrogen fixation figure would be higher by approximately 2.5 pounds, owing chiefly to much larger acreages of alfalfa, lespedeza, and soybeans. There is no sound basis upon which to estimate nonsymbiotic fixation. On the other side of the balance sheet, the nitrogen removed in harvested crops has increased by about 6 or 7 pounds per acre, owing chiefly to larger yields of grain crops, especially corn, and to the growing of larger acreages of legumes. It is impossible to give an accurate

estimate of the changes in erosion that have occurred during the period since 1930, but undoubtedly there has been a marked decrease as a result of the concentrated attack on this problem by federal and state agencies. Nitrogen losses by leaching and volatilization may also have decreased somewhat, but there are few facts upon which to base an estimate.

The nitrogen balance sheet for the United States, as presented in Table I, emphasizes the large annual net loss from soils; an up-to-date revision of the table, based on the most reliable information available, still shows a large loss but the figure is undoubtedly smaller. The mere fact that soils are further removed from the virgin state, and that the soil organic matter level is becoming more nearly stabilized at a lower level, assures some improvement in the nitrogen balance sheet. Improved farming practices are also undoubtedly exerting a major influence in the same direction.

A balance sheet of the type prepared by Lipman and Conybeare is interesting but of limited value in the present discussion because it deals with averages. When a soil nitrogen balance sheet is encountered that does not balance, usually general information, or average values, are inadequate for a solution of the enigma.

III. Lysimeter Experiments

A more accurate idea of what is happening to nitrogen in soils can be obtained by studies of individual experiments where soils have been maintained under near-natural conditions, and nitrogen income and outgo measured over a long period of years. In general, such data can be obtained only from lysimeters, where the drainage waters can be collected and analyzed. Field plot experiments furnish supplemental information, but, of course, accurate balance sheets cannot be constructed. An occasional pot experiment may also have been performed in such a manner that it supplies valuable information.

Reference will first be made to several lysimeter experiments reported from state experiment stations. Kohnke *et al.* (1940) give an excellent survey and discussion of the types of lysimeters that have been used for various purposes, and the results obtained. In nitrogen studies the filled-in type is usually used. Sometimes the soil is placed in layers corresponding to the natural soil horizons, but a few investigators have used top soil only. In either case, the soil is well mixed prior to being placed in the lysimeters so as to reduce sampling difficulties and to assure that the soils in all lysimeters are exactly alike. Since filled-in lysimeters are usually buried in soil or gravel in the open to near ground level, they present conditions for crop growth that vary little

from those in undisturbed soil, except for the differences in water penetration, water movement, and drainage conditions.

Lysimeter studies of most value in the present discussion are those (1) where nitrogenous fertilizers or manures were added in considerable quantity, (2) where no legumes were grown, (3) where all crops and soils were analyzed, and (4) where the experiment was continued for five years or longer, thereby reducing the errors due to sampling and analysis of the soils, plants, and leachates. In all such experiments erosion is, of course, eliminated.

All of the available data that meet the above requirements cannot be discussed here, but the most pertinent and representative results from the five experiment stations in this country where the most work of this type has been done will be considered.

1. Experiments at Ithaca, New York

During the period since 1910 several lysimeter experiments have been conducted at the Cornell Experiment Station. Concrete tanks were filled with layers of soil corresponding to the natural soil horizons.

In one experiment, reported by Bizzell (1943), a sandy loam soil was cropped for 15 years with two vegetable crops each year followed by a winter cover crop of rye. The treatments were replicated three times. Nitrogen was added in the forms of ammonia or nitrate to each vegetable crop at the time of planting. Table II shows the nitrogen balance sheet.

It will be observed that there was a marked decrease in soil nitrogen during the 15-year period, even though large quantities were added each year. Furthermore, only a little more than half of the nitrogen added or made available from the soil was recovered in the crop. About half of the remainder was found in the leachate, whereas the remaining portion was unaccounted for. The author states that this unrecovered nitrogen was presumably lost by volatilization. This loss occurred in a well-aerated sandy loam that was fertilized with excess nitrogen, intensively cultivated, and limed at intervals to keep the pH near 6.0. Wilson (1943) believed that such losses are commonly due to loss of nitrite in the exudate from plants or to loss of nitrogen gas formed as a result of the reaction of nitrite with amines in plant juices.

Another interesting Cornell lysimeter experiment, using Dunkirk silty clay loam, was reported by Bizzell (1944). In this experiment timothy was grown for 8 years, and sodium nitrate in varying amounts was added to duplicate lysimeters in three installments each year. The experimental procedures were similar to those used in the experiment just discussed. Table III shows the nitrogen balance sheet.

TABLE II

Recovery of Nitrogen from Ammonium Sulfate and Sodium Nitrate in a 15-Year Lysimeter Experiment[1] at Ithaca, New York (Results expressed on a per acre per year basis)

	Ammonium sulfate		Sodium nitrate	
	Lb. N	%	Lb. N	%
Nitrogen sources:				
Rain	6		6	
Fertilizer	143		143	
Soil	31		47	
Total	180	100	196	100
Nitrogen recoveries:				
Crops	94	52	110	56
Leachate	42	23	46	23
Total	136		156	
Not accounted for	44	24	40	20

[1] Cropping system: two vegetable crops and rye cover annually.

TABLE III

Recovery of Nitrogen in an 8-year Lysimeter Experiment[1] at Ithaca, New York (Results expressed on a per acre per year basis)

	Nos. 4 and 9		Nos. 5 and 10		Nos. 6 and 11		Nos. 8 and 12	
	Lb. N	%	Lb. N	%	Lb. N	%	Lb. N	%
Nitrogen sources:								
Rain	6		6		6		6	
Sodium nitrate	213		155		124		93	
Total	219	100	161	100	130	100	99	100
Nitrogen recoveries:								
Crops	154	70	121	75	98	75	78	79
Leachate	3	1	2	1	1	1	2	2
Soil	17	8	14	9	19	15	15	15
Total	174		137		118		95	
Not accounted for	45	21	24	15	12	9	4	4

[1] Cropping system: continuous timothy.

Under continuous timothy the soil showed a gain of 14 to 19 pounds of nitrogen annually, and the crop recovered 70 to 79 per cent of the nitrogen available to it. There was almost no loss of nitrogen in the drainage water, even where 213 pounds were added annually. The small loss that did occur was in the first year before the timothy was well established. Regardless of this, there was an unaccounted-for loss of nitrogen that varied from a negligible amount at the lowest rate of nitrate addition to 45 pounds per acre per year at the highest rate. Bizzell considered the losses to result chiefly from volatilization.

2. *Experiments at Geneva, New York*

Collison *et al.* (1933) reported the results of a 16-year lysimeter experiment conducted at Geneva, New York, in which soils of relatively low and high fertility were used without fertilizer additions. A 4-year rotation of timothy (2 years), barley, and wheat with two replications was used. The balance sheet for these data is given in Table IV.

TABLE IV
Nitrogen Balance Sheet for 16-Year Lysimeter Experiment[1] at Geneva, New York
(Results expressed on a per acre per year basis)

	Low-fertility soil		More fertile soil	
	Lb. N	%	Lb. N	%
Nitrogen sources:				
Rain	9		9	
Seed	2		2	
Soil	52		118	
Total	63	100	129	100
Nitrogen recoveries:				
Crops	44	70	69	53
Leachate	8	13	14	11
Total	52		83	
Not accounted for	11	17	46	36

[1] Cropping system: timothy (2 years), barley, and wheat.

Both soils lost large amounts of nitrogen during the experiment, and the loss increased with the fertility level. It is a little surprising that even though no fertilizer or manure was added, and the soils were in timothy for half of the time, there was an unaccounted-for loss of 17 to 36 per cent of the nitrogen available to the crop. The author concluded

that the only explanation for the large nitrogen deficits is that nitrogen escapes to the atmosphere.

3. *Experiments at Windsor, Connecticut*

Rather extensive lysimeter experiments (Jacobson *et al.*, 1948; Morgan and Jacobson, 1942; Morgan *et al.*, 1942a; and Morgan *et al.*, 1942b), using Merrimac sandy loam, have been reported from the tobacco station at Windsor, Connecticut. In one experiment various nitrogen sources were applied without replication to tobacco grown continuously for 10 years. The nitrogen recovery data are given in Table V.

TABLE V

Nitrogen Balance Sheet for 10-Year Lysimeter Experiment[1] at Windsor, Connecticut (Results expressed on a per acre per year basis)

	Three nitrates		Two NH_4^+ salts		Two ureas and cyanamid		Six organic fertilizers		No nitrogen	
	Lb. N	%	Lb. N	%	Lb. N	%	Lb. N	%	Lb. N	%
Nitrogen sources:										
Rain	4		4		4		4		4	
Fertilizers	200		200		200		200		0	
Soil	19		—		—		—		36	
Total	223	100	204	100	204	100	204	100	40	100
Nitrogen recoveries:										
Crops	93	42	73	36	88	43	79	39	20	50
Leachate	123	55	108	53	88	43	82	40	31	78
Soil	—		6	3	10	5	19	9	—	
Total	216		187		186		180		51	
Not accounted for	7	3	17	8	18	9	24	12	+11	0

[1] Continuous tobacco.

In this experiment with a very sandy soil that was heavily fertilized with nitrogen, it will be observed that usually more of the added nitrogen was recovered in the drainage water than in the crop. Nearly all of the added nitrate was accounted for but there was an average unaccounted-for loss of about 10 per cent of the nitrogen added in the other forms.

In a similar experiment, calurea was added to cylinders at the rate of 200 pounds of nitrogen per acre annually for 10 years and various

cropping systems compared, using duplicate treatments. Table VI gives the nitrogen recovery data.

TABLE VI

Nitrogen Balance for a 10-Year Lysimeter Experiment at Windsor, Connecticut, Where the Soils Were Fertilized with Calurea
(Results expressed on a per acre per year basis)

	Fertilized with calurea								No nitrogen			
	Fallow		Tobacco		Tobacco + oat cover		Grass sod		Tobacco		Grass sod	
	Lb. N	%	Lb. N	%	Lb. N	%	Lb. N	%	Lb. N	%	Lb. N	%
Nitrogen sources:												
Rain	4		4		4		4		4		4	
Fertilizer	200		200		200		190		0		0	
Soil	67		28		2		—		51		40	
Total	271	100	232	100	206	100	194	100	55	100	44	100
Nitrogen recoveries:												
Crops	0	—	90	39	94	46	77	40	19	34	16	36
Leachate	225	83	97	42	48	23	28	14	29	53	6	14
Soil	—		—		—		8	4	—		—	
Total	225		187		142		113		48		22	
Not accounted for	46	17	45	19	64	31	81	42	7	13	22	50

The average percentage of added nitrogen, plus that released from the soil that was unaccounted for, varied between 17 and 42 per cent for the fertilized soils, and was either 13 or 50 per cent for the unfertilized soils. It is especially surprising that the lowest recovery was with grass sod. Most investigators have observed little or no losses with sod crops, and some marked gains, supposedly due to biological nitrogen fixation, have been reported. The recoveries of nitrogen were the same where tobacco was grown as where the soil was kept fallow. The introduction of an oat cover crop following tobacco made the nitrogen balance less satisfactory, even though this additional crop reduced the nitrogen content of the leachate.

Other experiments similar to those reported in Table VI, where mixed sources of nitrogen were used instead of calurea, gave recoveries that agreed closely with the calurea data. These results are at considerable variance with most other lysimeter data.

4. Experiments at Knoxville, Tennessee

Lysimeter experiments on the recovery of fertilizer nitrogen from soils have been reported from the Tennessee Experiment Station. In the two experiments of most interest in the present discussion the soils, unfortunately, were not analyzed at the end of the experiments. The recovery of added nitrogen must, therefore, be based on the difference between the nitrogen in the drainage waters from fertilized and unfertilized soils.

In these experiments 989 pounds of nitrogen per acre in the form of nitrate (Mooers *et al.*, 1927), or of ammonium salts (MacIntire *et al.*, 1952), were added in a single application to an uncropped silt loam in lysimeters 6 feet deep (Table VII).

TABLE VII

Recovery of Nitrogen from Uncropped Cumberland Silt Loam in Lysimeters at the Tennessee Experiment Station

	Nitrogen in leachates			
Forms of nitrogen added	Total, lb. per acre	From fertilizer, lb. per acre	Recovery, %	Average recovery, %
First expt.[1]—5 years				
No nitrogen	68.3			
Calcium nitrate	889.8	821.5	83.1	
Magnesium nitrate	871.1	802.8	81.2	
Sodium nitrate	987.4	919.1	93.0	85.8
Second expt.[1]—12 years				
No nitrogen	372.8			
Ammonium chloride	1160.1	787.3	79.6	
Ammonium phosphate	1111.3	738.3	74.7	
Ammonium sulfate	1224.7	851.9	86.2	80.2

[1] Single additions of 989 lb. N per acre. Three replications.

The recovery of added nitrate nitrogen averaged 86 per cent, and that of ammonia nitrogen 80 per cent. The ammonia nitrogen was of course removed as nitrates following nitrification. Loss of a fair percentage of the nitrogen by volatilization is indicated.

All of the experiments discussed above have dealt with soils in the humid regions. Similar data from the semiarid and irrigated regions, where there is little or no leaching, are sparse. Only one such lysimeter experiment, namely, that reported by the California Experiment Station, will be discussed here in detail.

5. *Experiments at Riverside, California*

The experiment at California, described by Chapman *et al.* (1949) and by Broadbent and Chapman (1950), is being conducted in lysimeters that are 10 feet in diameter and 4 feet deep. These were filled with a Sierra loam top soil having a nitrogen content of 0.04 per cent. The data for the six lysimeters that were cropped to Sudan grass for the 15-year period are given in Table VIII.

TABLE VIII

Nitrogen Balance Sheet for 15-Year Lysimeter Experiment[1] at Riverside, California (Results expressed on a per acre per year basis)

	No cover crop 2.5 tons straw						Mustard cover crop turned under no straw					
	No N		100 lb. N		200 lb. N		No N		100 lb. N		200 lb. N	
	Lb. N	%	Lb. N	%	Lb. N	%	Lb. N	%	Lb. N	%	Lb. N	%
Nitrogen sources:												
Rain and irrigation	8		8		8		11		13		13	
Fertilizer[2] and straw	32		131		237		0		100		200	
Soil	96		96		71		120		75		48	
Total	136	100	235	100	316	100	131	100	188	100	261	100
Nitrogen recoveries:												
Crop	84	62	140	60	171	54	87	66	139	74	192	74
Leachate	51	37	73	31	113	36	18	14	31	16	40	15
Total	135		213		284		105		170		232	
Not accounted for	1	1	22	9	32	10	26	20	18	10	29	11

[1] Cropping system: sudan grass with and without mustard cover crop.
[2] Nitrogen supplied as calcium nitrate; no replication.

In all cases the soil lost much nitrogen, and there was failure to account for all of the available nitrogen added or released from the soil. This unaccounted-for nitrogen varied between 1 and 20 per cent for the 15-year period. For the first 10 years of the experiment (Chapman *et al.*, 1949) there were indications that the losses by volatilization from some lysimeters were greater than these values. The earlier results also suggested that nonsymbiotic nitrogen fixation was of considerable importance where carbonaceous plant materials were present, but the values for the 15-year period do not substantiate this view.

These data emphasize some of the limitations of the lysimeter technique, especially when the treatments are not replicated. Broadbent and Chapman (1950) point out that the errors of soil sampling were large. This was due in part to the absence of leaching during the last 5 years of the experiment, which permitted some accumulation and uneven distribution of nitrates. In addition, there was, unfortunately, an accumulation of 610 to 855 pounds per acre (4-foot depth) of nitrate-nitrogen in the soils at the time of starting the treatments. This nitrate was formed from the oxidation of the soil organic matter during the 7-year period that the soil was allowed to settle following the filling of the lysimeters.

Results obtained in lysimeter experiments at the Arizona Experiment Station (Smith, 1944) are in some respects comparable to those obtained at California. In the Arizona experiment a Gila loam and a Mohave clay, cropped to nonlegumes for 12 years (unreplicated), showed a large loss and a large gain in nitrogen, respectively. However, after 18 years, when additional soil analyses were made, the average yearly gaseous loss in the one soil, and gain through bacterial fixation in the other, were greatly reduced. Construction of accurate nitrogen balance sheets for the 18-year period is not possible from the limited data published to date (Smith, 1953).

6. *General Remarks*

In considering lysimeter experiments it is well to bear in mind that a high degree of accuracy in such experiments cannot be expected. Chief among the sources of error are the inaccuracies of soil sampling and the errors involved in the storage and analysis of the leachates. In addition, few experiments have been adequately replicated. Fortunately, the errors of analysis of the soils and crops need not be great, since the large numbers of analyses required assures that the individual plus and minus errors will largely cancel out. Regardless of their limitations, lysimeters do furnish valuable information that cannot be obtained by other methods.

The experiments discussed above bring out the following facts:

1. Crops commonly recovered only 40 to 75 per cent of the nitrogen that was added or made available from the soil. Low recoveries were usually obtained where large additions of nitrogen were made, where the soils were very sandy, and where the crop was not adequate to keep the nitrogen low.

2. The nitrogen content of most soils decreased regardless of how much was added as fertilizer unless the soil was kept in uncultivated crops.

3. A large proportion of the nitrogen not recovered in the crop was

found in the leachate, but substantial unaccounted-for losses occurred in most lysimeters. Nitrogen gains were few.

4. The magnitude of the unaccounted-for nitrogen was largely independent of the form in which the nitrogen was supplied, whether as nitrate, ammonia, or organic nitrogen.

5. Unaccounted-for nitrogen was commonly slightly higher in cropped soils than in fallow soils. Fifty-one lysimeters that received nitrogen and were planted to nonlegume crops showed an average unaccounted-for loss of 20 per cent of the total available nitrogen; the corresponding figure for 106 uncropped soils was 12 per cent. The average value is near 15 per cent. A small portion of the loss from the cropped lysimeters can be accounted for as due to insects and birds, loss of leaves and pollen, and leaching of nitrogen from the leaves onto soil outside the lysimeters. Any nonsymbiotic nitrogen fixation that may have occurred would of course increase the loss figures for both cropped and uncropped soils. These data constitute strong evidence that nitrogen losses from normal, well-aerated soils, by volatilization, are not negligible.

The statement is frequently made that lysimeter experiments are too artificial to show what happens under normal conditions. Drainage losses seem to be much too high, especially if filled lysimeters are used. Although this criticism is doubtless justified in many cases, this fact does not seriously affect the value of the data for use in the present discussion of the nitrogen balance enigma.

IV. Field Experiments

Accurate soil nitrogen balance sheets cannot be constructed from experimental data obtained in ordinary field experiments. This is due chiefly to lack of knowledge of the quantity of nitrogen removed annually by leaching and erosion, frequent failure to analyze the crops for total nitrogen, and the uncertainty as to the contribution that the subsoil has made to the feeding of the crop. Nevertheless, field experiments do supply information that is sufficiently quantitative to show the magnitude of the main soil losses or gains. Two such experiments will be discussed below in some detail, and reference will be made to several others that are of general interest.

1. Experiments at Rothamsted, England

The experiments conducted on the Broadbalk wheat fields at Rothamsted furnish considerable information on nitrogen losses from soils because rain gauges are located near the plots. Table IX, constructed from unreplicated data given by Russell (1950), gives the pertinent information.

TABLE IX

Losses of Nitrogen from Soils at Rothamsted
(Figures are expressed in pounds of nitrogen per acre per year)

	Broadbalk wheat plots 1865–1914			Drain gauges 1870–1915, no N and no crop
	Plot 3 No N	Plots 7 and 13 Am. sulfate	Plot 2B Farm manure	
Nitrogen sources:				
Rain and seed	7	7	7	5
Fertilizer or manure	0	86	201	0
Soil, top 9 inches	8	3	—	26
Total	15	96	208	31
Nitrogen recoveries:				
Crop	17	45	50	—
Leachate	a	a	a	27
Soil, top 9 inches	—	—	15	—
Total	17	45	65	27
Nitrogen not accounted for	+2	51	143	4

a = Not determined.

On the wheat field, where no nitrogen was added, the nitrogen in the crop accounts for all that was added in the rain plus that released from the soil. For a similar soil maintained uncropped in a drainage gauge (lysimeter) practically all of the released nitrogen was recovered in the drainage waters. Evidently under these conditions if a crop was present, it got the nitrogen; otherwise it was lost in the drainage. There is no evidence for gaseous losses of nitrogen at this low nitrogen level, or for nitrogen fixation. One process could, of course, offset the other.

Where nitrogen was added as fertilizer or manure, the quantity not accounted for was large. For ammonium sulfate it was about 50 per cent and for farm manure, at a much higher rate of nitrogen application, it was near 70 per cent. Most of this unrecovered nitrogen was probably lost by leaching, just as occurs in lysimeter experiments. In addition, appreciable losses both as ammonia and as free nitrogen gas would be expected from the manured plot, and to a lesser extent from those receiving ammonium sulfate.

2. *Cylinder Experiments at New Brunswick, New Jersey*

Another interesting set of experiments that serves as a tie-in between lysimeter and field experiments is the 40-year cylinder experi-

ment (Prince *et al.*, 1941) conducted at the New Jersey Experiment Station. In these experiments there was no provision for catching the drainage waters. The subsoil was merely removed and mixed, the 4-foot cylinders put in place, and the subsoil replaced. Eight inches of Penn loam top soil was then added.

One portion of the cylinders was fertilized regularly with different nitrogen sources, including manure, and cropped to a 5-year rotation of corn, oats, oats, wheat, and timothy. The treatments were not replicated. Some of the soils were limed regularly to keep the pH in the range of 5.7 to 6.7; the others were left unlimed and the pH dropped to 4.1 to 5.2. Table X gives the soil nitrogen recovery data for a portion of the treatments in the limed series.

TABLE X

Recovery of Nitrogen from Limed Soils in the New Jersey Cylinder Experiments
(Figures are expressed in pounds of nitrogen per acre per year)

	No N	Manure	Sodium nitrate	Ammonium sulfate	Dried blood
Nitrogen sources:					
Rain	5	5	5	5	5
Fertilizer or manure	0	129	50	51	50
Soil	62	6	54	42	37
	—	—	—	—	—
Total	67	140	109	98	92
Nitrogen recoveries:					
Crop	32	65	61	52	51
	—	—	—	—	—
Per cent of nitrogen available to crop not accounted for	52	54	44	47	45

The average recovery in the crop of the nitrogen available to it was slightly more than 50 per cent. This recovery figure agrees closely with the values commonly obtained in lysimeter experiments. The unrecovered nitrogen was lost either in the drainage waters or as gas.

Nitrogen recovery data for the unlimed soils of the New Jersey cylinder experiment are given in Table XI.

In the unlimed series the crop growth was less than in the presence of lime, and there was a somewhat greater release of nitrogen from the soil. Only about 29 per cent of the available nitrogen was recovered in the crop. This value is even lower than that obtained in the Connecticut lysimeter experiments, where much larger quantities were added to a sandy soil cropped to tobacco. Again, we assume, as Lipman and Blair

TABLE XI

Recovery of Nitrogen from Unlimed Soils in the New Jersey Cylinder Experiments
(Figures are expressed in pounds of nitrogen per acre per year)

	No N	Manure	Sodium nitrate	Ammonium sulfate	Dried blood
Nitrogen sources:					
Rain	5	5	5	5	5
Fertilizer or manure	0	129	50	51	50
Soil	69	19	59	63	66
	—	—	—	—	—
Total	74	153	114	119	121
Nitrogen recoveries:					
Crop	21	60	36	26	32
	—	—	—	—	—
Per cent of nitrogen available to crop not accounted for	72	61	68	78	73

(1916) had earlier, that most of the unrecovered nitrogen escaped through leaching. Low crop yields, due to high acidity, would of course favor leaching. It is also well to bear in mind that nitrites are very unstable in acid media and at pH values below 5.0 nitrogen may escape readily as nitric oxide. This may have happened to some extent in these New Jersey soils.

3. *Miscellaneous Experiments*

Field experiments, other than the cylinder experiments discussed above, were also conducted at the New Jersey Experiment Station by Lipman *et al.* (1928) during the period 1908 to 1927, using a 5-year rotation of corn, oats, wheat, and timothy, with various fertilizer additions. One set of plots was limed to near neutrality and the other was left unlimed. The average recoveries of added nitrogen in the crops for successive 5-year periods in the limed soils were 30.6, 26.0, 20.2, and 31.5 per cent; the corresponding values for the unlimed soils were 26.5, 22.3, 23.6, and 30.4 per cent. The over-all nitrogen recoveries during the 20-year period from the limed soils for the different nitrogen sources were: calcium nitrate and ammonium sulfate 42; calcium cyanamid 36, sodium nitrate 33, fish scrap and tankage 26, and manure 12 per cent; on the unlimed soils the recoveries in the same order were 32, 21, 33, 37, 37, 21, and 17 per cent. During the period of the experiment manure increased the nitrogen content of the soil about 0.03 per cent, but the other materials had little effect.

White *et al.* (1945) have emphasized the importance of nitrogen fixation in grassland soils in Pennsylvania. In the Jordan plots at the end of 72 years the unfertilized grassland soils show a nitrogen level 68 per cent above that of the unfertilized cultivated soils. However, anyone who has seen these plots must be greatly impressed with the extent to which erosion has removed the top soil except from the sodded areas.

In earlier field studies at the Pennsylvania Station, White and Holben (1931) showed the marked unaccounted-for losses in nitrogen that occurred during the early years of field experiments. Later there were some gains which the authors attributed to nonsymbiotic nitrogen fixation. Interpretation of these data is complicated by the presence of a clover-timothy mixture in the 4-year rotation used. Of the nitrogen applied as sodium nitrate, 58.8 to 80.3 per cent was not recovered in the crop or soil; the percentage recovery decreased as the quantity added increased.

Salter and Green (1933) estimated that in Ohio one crop of corn reduced the soil nitrogen by 2.97 per cent; the value for wheat was 1.56 per cent, and for oats, 1.45 per cent.

Woodruff (1949) gives data from the Sanborn Field at Columbia, Missouri, where corn was grown, showing a decrease in nitrogen in the surface soil from 3400 to 1410 pounds per acre during the period 1888 to 1948. The decrease during the last 33 years was only 390 pounds. He calculates that the annual accretion of nitrogen by the soil during the 33 years, after allowance for crop removal, was 20.5 pounds per acre. He states that the sources of this nitrogen are rainfall and biological activity. Similar treatment of the data from the Morrow plots at Urbana, Illinois, gives an almost identical figure for the continuous corn plot. If these data are correct, there was, presumably, no appreciable loss of nitrogen by leaching or by volatilization, or if they occurred, fixation by nonsymbiotic bacteria more than compensated for these losses. The data clearly emphasize that as the equilibrium level of soil nitrogen is approached, the unaccounted-for nitrogen losses become less and less, unless fertilizers or animal manures are added. However, before accepting the idea that nonsymbiotic fixation is as important as Woodruff's calculations would indicate, it should be realized that during the 33 years it is assumed that subsoil nitrogen remained constant. A decrease in subsoil nitrogen too small to measure accurately would account for all or most all of the fixation that the calculations indicate. Under a continuous corn cropping system where nitrogen is increasingly limiting growth one would certainly expect the crop to utilize some of these subsoil reserves.

In field studies with wheat at Iowa, Black *et al.* (1946) obtained

nitrogen recoveries in the grain and straw of 57, 40, and 28 per cent from nitrogen applications of 32, 64, and 128 pounds per acre, respectively. Even if allowance is made for the nitrogen in the roots, it is obvious that the percentage recovery is far below 100 per cent.

Studies by Smith *et al.* (1954) with the Blackland soils of Texas show that during 70 years of cultivation these soils lost 50 per cent or more of their surface organic matter and also large quantities from the subsoil.

Finnell (1933) states that in the Oklahoma soils studied the average yearly decline in nitrogen in the 0 to 6-foot soil layer during the first 22 years after plowing the native sod was 50 pounds. Approximately 20 pounds of this loss was through crop removal, leaving 30 pounds wasted annually. Continuous cropping resulted in the concentration of nitrogen nearer the surface than did systems involving summer fallowing.

In Kansas (Dodge and Jones, 1948; Myers *et al.*, 1943; Metzger, 1939) when the soils were first put under cultivation the loss of nitrogen was greatly in excess of its removal by crops, but in more recent years the two values have tended to agree more closely.

The loss of soil nitrogen from the experimental plots at the South Dakota Experiment Station (Puhr, 1945) between 1915 and 1939 averaged 16 per cent. The loss from the soils not fertilized with nitrogen exceeded the nitrogen removed in the crop by about 50 per cent. The addition of sodium nitrate did not help in the maintenance of the soil nitrogen level nor greatly increase the crop yields. Under these conditions about 80 per cent of the fertilizer nitrogen added during the 25-year period was not accounted for. Data reported (Peevy *et al.*, 1940) for Iowa soils are similar to those from South Dakota, but the portion of the loss that can be accounted for in the crops removed is not given.

Nitrogen analyses (Allison and Sterling, 1949) of soils taken from representative plots at the experiment station at Mandan, North Dakota, show that where no legumes were grown or nitrogen additions made, surface soils lost an average of 28 per cent of their original nitrogen during 33 years of cropping under dry land conditions where little or no leaching occurred. Allowing for nitrogen brought down in the rainfall, this means that about twice as much nitrogen was lost from the soil as was removed in crops.

Sievers and Holtz (1922) found that in the state of Washington large losses of nitrogen from semiarid soils occurred even where drainage losses were negligible. Other work at the same station by Wheeting (1937), but with upland soils from the western part of the state,

led to a different conclusion. A study of 73 pairs of soil samples taken from cultivated and virgin areas showed an average increase of 28 per cent in organic matter as a result of cropping for 45 years. The increase was largest where the soil management system provided for a return of a considerable quantity of plant residues. Some of the increases are probably due to a change from a forest-type vegetation to a cereal-type. More recent studies (Smith and Vandecaveye, 1946) of soils from the Palouse region of the state of Washington show many negative nitrogen balance figures, especially where considerable nitrogen was applied. A portion of this loss was due to leaching and the remainder was by volatilization. From time to time workers at this station have emphasized the probable importance of nonsymbiotic nitrogen-fixing organisms in the soils of the Northwest but proof of this is lacking.

In two dry-farming regions of Utah that had been farmed for 25 and 40 years, Bracken and Greaves (1941) found that the nitrogen removed in the crop accounted for only 28.7 and 33.9 per cent, respectively, of that lost from the soil. Since leaching and erosion were not important, they considered that the major part of the unknown loss occurred through volatilization.

Studies of the soils of Manitoba, Saskatchewan, and Alberta in western Canada, reported by Shutt (1925), show that during the first 22 years of cropping, the soils lost about 75 pounds of nitrogen per acre annually in addition to that removed in the crops. The unaccounted-for nitrogen was about twice as great as that in the crop. Later calculations by Caldwell *et al.* (1939) agree closely with the values given by Shutt. A recent report by Hill (1954) from western Canada shows that wheat yields on summer fallow in grain rotations are being maintained after 40 years of cropping without fertilizer or manure. He states, however, that at the Lethbridge Station in Alberta the average losses in soil nitrogen since 1910 have been 25 per cent.

Under many cropping systems where irrigation is practiced it is common practice to add unusually large quantities of nitrogen annually, and the unaccounted-for nitrogen is likely to be a large percentage (Chapman, 1951; Furr and Barber, 1950; Greaves and Hirst, 1943) of that added. Presumably most of this nitrogen is removed in the drainage waters, but, as Chapman emphasizes, gaseous losses may also be important.

Many other field experiments might be cited, but the ones mentioned are adequate to show that nitrogen recovery results, obtained in field experiments, are not greatly different from those reported from lysimeters. There is, however, one important difference between experimental data and practical results that is sometimes overlooked. In

most lysimeters the water that falls on the soil stays there and moves downward. Likewise, experimental field plots are usually located on nearly level soil where the runoff is below average. Under practical field conditions, especially where the soil surface is rolling, it would be logical to expect less loss of nitrogen by leaching than many of the experiments discussed here, especially the lysimeter data, would indicate. A decreased rate of removal would give the crop more time to assimilate it. On the other hand, it would allow more opportunity for gaseous losses to occur.

V. Greenhouse Experiments

As a supplement to the studies discussed above, it is interesting to see what information greenhouse studies can contribute to the solution of the soil nitrogen balance enigma. The ideal experiment for this purpose is one where several applications of nitrogen were made to the same soil, several nonlegume crops grown, and all crops and soils analyzed. Few greenhouse experiments reported in the literature meet these requirements. Only three experiments will be discussed here, and one of these (Mann and Barnes, 1951) only partially meets the above requirements.

1. Experiments at Beltsville, Maryland

Pinck *et al.* (1948a) reported an experiment, extending over a period of 4 years, in which five successive green manure crops were grown on a loamy sand to various stages of maturity, and then incorporated in the soil. After each green manure crop, wheat or sudan grass was grown to the stage where heads were forming and the above-ground portion was removed. Urea was added at different rates, part to grow the green manure crop and part to grow the crop to be harvested. All treatments were made in duplicate, and all crops and soils were analyzed for total nitrogen. In Fig. 1 the amount of nitrogen recovered in the crops and soils from all of the treatments is plotted against total nitrogen added.

The regression line in Fig. 1 shows that for every unit of nitrogen added above about 50 pounds per acre per harvested crop, the unaccounted-for nitrogen amounted to 18 per cent; the over-all loss for the higher rates of application was near 14 per cent. It is uncertain whether the few small gains in nitrogen at the lower nitrogen levels are due to nonsymbiotic fixation or are merely indicative of normal experimental error.

In another greenhouse experiment (Pinck *et al.*, 1948b), which lasted for 3 years, the experimental procedure was similar to that in

the experiment just discussed, except that the green crops were grown in the field and added to the greenhouse soil together with urea. A few pots received applications of either urea, sodium nitrate, or cottonseed meal without additions of plant materials. For all treatments five successive additions were made in duplicate and a crop of either wheat or sudan grass was grown after each addition. These five crops were harvested and analyzed for total nitrogen. The soils were also carefully

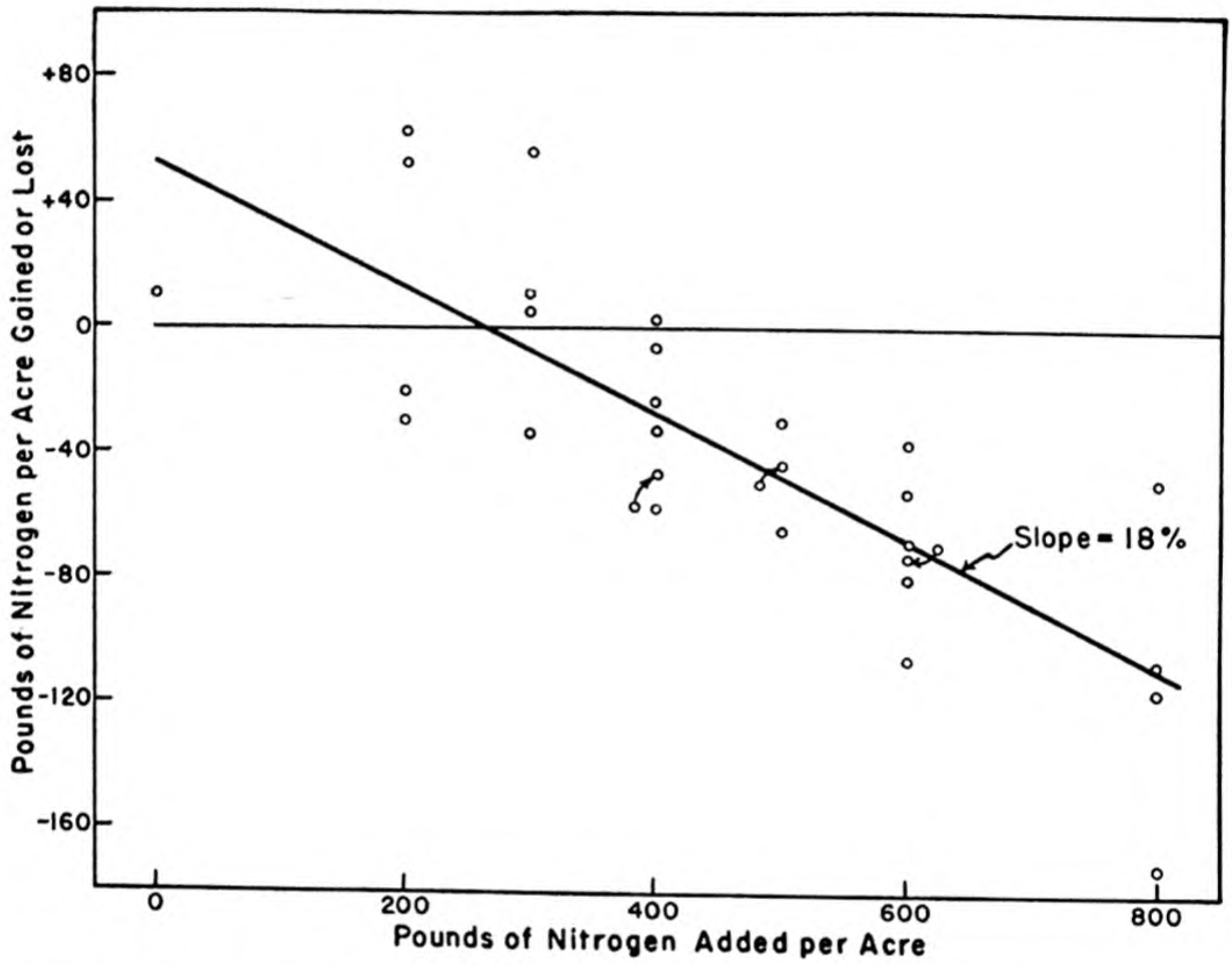

FIG. 1. Nitrogen gains and losses in a 4-year greenhouse experiment where five green manure crops and five harvested crops were grown, urea being the nitrogen source applied (Pinck *et al.*, 1948a).

sampled and analyzed. Figure 2 shows the nitrogen gains and losses that occurred.

The straight-line graph of these data shows that for every unit of nitrogen added above about 60 pounds per acre per harvested crop, regardless of its form, the unaccounted-for nitrogen amounted to 14 per cent; the over-all loss for the larger nitrogen additions was near 11 per cent. A smaller loss in this experiment than in the one reported in Fig. 1 might be expected, since a large percentage of the nitrogen in this second experiment was supplied as plant materials. Until such nitrogen is converted into either ammonia, nitrites, or nitrates, appreciable losses by volatilization are very unlikely.

The loss of nitrogen in the two greenhouse experiments was appreciably lower than the 20 per cent figure for the cropped lysimeters.

In the greenhouse studies there were, of course, no leachates to collect and analyze, and soil sampling could be done much more accurately. There was also less opportunity for the numerous small losses, particularly of plant parts, that can occur in the open. On the other hand, there is a greater chance for denitrification in the greenhouse owing to possible temporary waterlogging of the soils. Such denitrification can

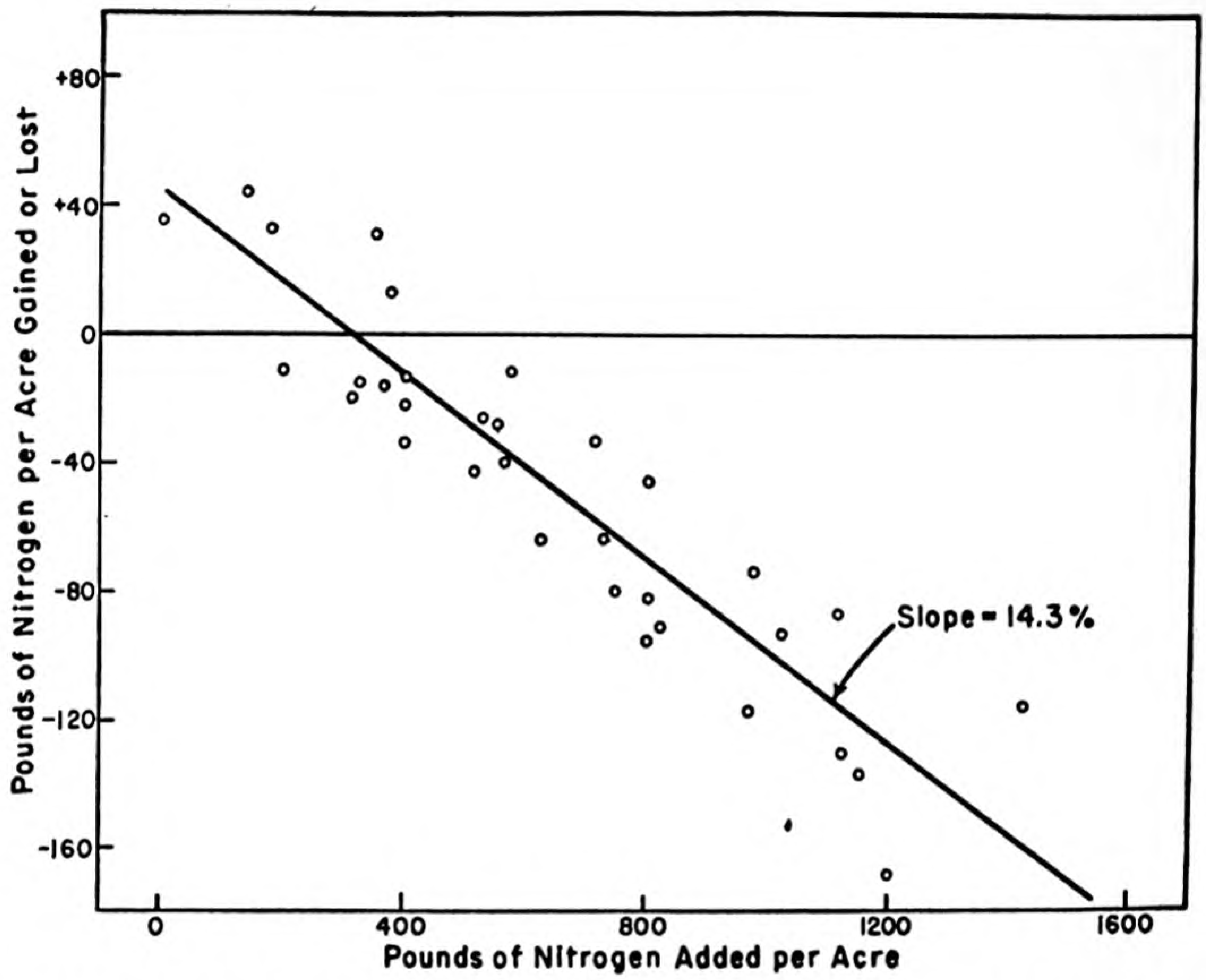

FIG. 2. Nitrogen gains and losses in a 3-year greenhouse experiment, where green crops together with fertilizer nitrogen were added, and five crops harvested (Pinck *et al.*, 1948b).

occur only if nitrates or nitrites are present. In the two experiments of Pinck *et al.*, there was little or no opportunity for either of these compounds to accumulate.

2. *Experiments at Woburn Experimental Station, England*

Mann and Barnes (1951) have reported greenhouse pot experiments, conducted at the Woburn Experimental Station, which were designed to account for the nitrogen added in the forms of plant residues and ammonium sulfate. The rates of application varied between 37 and 150 pounds of nitrogen per two million pounds of a loam soil. Two crops of barley were grown and the soils were leached at various times. All crops, leachates, and soils were analyzed. After 18 months the nitrogen unaccounted for in two experiments averaged 40 per cent for that added in the form of tare residues, 43 per cent for mustard residues, and 51 per cent for ammonium sulfate. The authors emphasize the limitations

of the analytical procedures, but, nevertheless, consider that the data indicate marked gaseous losses of nitrogen. In the light of the similar but more extensive experiments of Pinck *et al.* (1948a, b), discussed above, as well as of the greenhouse experiments of Goring and Clark (1948), it seems doubtful if the nitrogen losses were as large as the English work would indicate. Very likely a considerable portion of this unaccounted-for nitrogen still remained in the soil combined with carbon, and also fixed in an unavailable and difficultly exchangeable form in the soil (Allison *et al.*, 1953). The lower recovery obtained with ammonium sulfate than with the organic nitrogen sources would indicate considerable fixation of ammonium ions by the clay minerals. At the low levels of nitrogen added it would, however, be impossible to determine this accurately by ordinary analytical procedures not involving tracer techniques.

VI. Losses of Nitrogen by Volatilization

Since volatilization of nitrogen is apparently important and not well understood, it is well to consider the channels or mechanisms by which these losses occur. For ease of discussion these are grouped below under five headings, with an additional general section following.

1. Losses as Ammonia

There is essentially universal agreement among investigators (Gerretsen, 1950; Jewitt, 1942; Kappen *et al.*, 1943; Lehr, 1950; Martin and Chapman, 1951; Steenbjerg, 1944; Tovborg-Jensen and Kjaer, 1948; van Schreven, 1950; and Willis and Sturgis, 1944) that under suitable conditions ammonia is rapidly lost from soil by volatilization. Such losses may amount to 25 per cent or more of the ammonia added or formed.

The main established facts regarding ammonia volatilization are: (1) barely detectable losses may occur at pH 6 to 7 but losses increase markedly at higher pH values; (2) losses from wet soils are likely to be small but are very high if an alkaline soil, containing much ammonia near the surface, is dried; (3) losses increase with temperature; (4) losses are greatest in soils of low exchange capacity; and (5) losses may be high where nitrogenous organic materials are allowed to decompose on or near the soil surface, even if the soil is acid, since the ammonia formed raises the pH locally.

Almost invariably where manure has been used in long-time field experiments, such as those at Rothamsted, the recovery of the nitrogen has been low. One of the main reasons for this, as has frequently been shown (Heck, 1931; and Lindhard, 1954), is volatilization of ammonia,

especially where the manure is not incorporated into the soil immediately after spreading.

2. *Losses as Nitric Oxide by Chemical Reaction*

Nitric oxide, as is well known (Allison and Doetsch, 1951; Fraps and Sterges, 1939; Gerretsen, 1949, 1950; Robinson, 1923; Turchin, 1936), is formed rapidly from nitrous acid under acid conditions. Such decomposition of nitrites is appreciable at a pH of about 5.0 (Allison and Doetsch, 1951), and the rate and extent of decomposition are greatly accelerated with increase in acidity. Much of the nitric oxide formed is likely to be oxidized chemically to nitric acid or to be absorbed by soil organic matter, but some of this gas escapes to the air. This lack of stability of nitrous acid is doubtless one of the main reasons for negative nitrogen balance sheets commonly obtained when working with acid soils. Quantitative data on the magnitude of such losses in soils are, however, not available. Microorganisms can contribute to this source of nitrogen loss through the formation of nitrites, but probably do not produce much nitric oxide directly (Wijler and Delwiche, 1954). Baalsrud and Baalsrud (1954) have, however, reported that in the presence of thiosulfate, nitrite is rapidly decomposed to nitric oxide, and may later be reduced to molecular nitrogen, by *Thiobacillus denitrificans*.

Mention should also be made of the work of Madhok and Uddin (1946), who report that nitrous acid may also be lost from soils of pH above 7. They state that the reaction is chemical and is catalyzed by certain soil constituents. The information presented is insufficient for an evaluation, but any such losses that might occur are not likely to be of any appreciable practical importance.

3. *Losses as Nitrogen Gas by Chemical Reaction*

Many claims, reviewed elsewhere (Allison and Sterling, 1948; Wilson, 1943), have been made that in both plant juices and soils nitrous acid reacts with reduced forms of nitrogen, such as amino acids and ammonia, to form nitrogen gas. The reaction is a strictly chemical one but the reactants may be formed in nature chiefly by biological agencies. This reaction, which is utilized in the Van Slyke apparatus for the quantitative determination of amino acids, is as follows:

$$RNH_2 + HNO_2 \rightarrow ROH + H_2O + N_2$$

It should be noted that the nitrogen gas is derived in equal amounts from the two reacting compounds. In the Van Slyke apparatus the re-

action is carried out in the presence of glacial acetic acid and in an atmosphere of nitric oxide. Under such conditions it proceeds rapidly and goes to completion.

The conditions in soil are obviously very different from those given above, and there has always been considerable doubt as to whether this reaction could occur to any appreciable extent in either soils or plant juices. Recent work (Allen and van Niel, 1952; Allison and Doetsch, 1951; Allison *et al.*, 1952; Jones, 1951; Wijler and Delwiche, 1954) has shown, in fact, that there is little likelihood that this reaction occurs to any appreciable extent under conditions commonly occurring in nature. At pH values where the reaction can occur at an appreciable rate, namely 5 or lower, conditions for nitrite formation by both oxidation and reduction are not favorable. Even if formed, the nitrites are much more likely to decompose to form nitric oxide than they are to react with amines or ammonia to form nitrogen gas. It is concluded, therefore, that there is little or no evidence at present that nitrogen is lost in more than minor quantities from either soils or plants by the so-called Van Slyke reaction.

In this connection, the recent paper of Wahhab and Uddin (1954) needs discussion. They added sodium nitrite and ammonium sulfate in various proportions and concentrations to alkaline soils and solutions and determined the loss of nitrogen. At low concentrations there was no loss of nitrogen by ion interaction, whereas at higher concentrations elemental nitrogen was lost, but only after desiccation. In one soil, with a pH of 10.1, they report that the loss of nitrite-nitrogen, due to interaction with ammonia, was very high. The authors imply that their results differ from those of other workers, mentioned above, who have recently found little evidence for losses of nitrogen by the Van Slyke reaction at pH values below 7. Actually, it would seem that there is no conflict, since the Van Slyke reaction can occur only where free nitrous acid (not nitrite ion) is present. The losses reported by Wahhab and Uddin must, therefore, have been brought about by another mechanism. This other mechanism was probably the formation of ammonium nitrite from the rearrangement of the ions of the added salts. This compound decomposes readily to nitrogen gas, water, and sometimes traces of ammonia, especially at temperatures of 50° C. and above. Whether this mechanism is the correct one remains to be established, but, whatever it is, losses of the interaction type that they report cannot be of much practical importance under normal field conditions; the concentrations of NO_2^- and NH_4^+ are too low for much of the nitrogen to be volatilized.

4. Losses as Nitrous Oxide and Nitrogen Gas by Bacterial Denitrification

It seems to be generally agreed among soil bacteriologists that most of the gaseous losses of nitrogen from soils, other than as ammonia, are brought about by denitrifying bacteria. The chief product of the reaction has been generally assumed to be nitrogen gas, although a few early workers (Beijerinck and Minkman, 1910; Suzuki, 1911) had reported finding nitrous oxide as a common product of bacterial denitrification. The recent work of Adel (1951), Arnold (1954), and Wijler and Delwiche (1954) has substantiated this early work. Both Adel and Arnold consider that the soil is the probable source of the nitrous oxide found in the atmosphere. Wijler and Delwiche (1954) found that this oxide was the major product of denitrification under most soil conditions. It was, however, readily reduced to free nitrogen gas in soils of pH 7 and above, but not under acid conditions. Arnold (1954) suggests the possibility that nitrous oxide may not only be formed during the reduction of nitrate, but may also appear during the oxidation of ammonium ions, when the oxygen supply is limited. The work of Sacks and Barker (1952) with *Pseudomonas denitrificans* shows, however, that under some conditions, and with some organisms, nitrogen gas is likely to be the main product of denitrification. In their experiments no nitrous oxide accumulated, and they could find no evidence that this gas is a normal precursor of N_2 in the reduction of nitrite. The mechanism of the formation of nitrous oxide deserves further study.

Under strictly anaerobic soil conditions nitrite- and nitrate-nitrogen may be almost completely volatilized in a comparatively short time. The experiments of Jones (1951) show this strikingly. Where sodium nitrate was added to an air-dry soil, which was then brought up to optimum moisture and incubated anaerobically, about 80 per cent of the nitrogen was volatilized in 3 days. Denitrification proceeded almost as fast where the sole source of energy was soil organic matter as where 0.5 per cent sucrose was added. The rate of gas evolution would undoubtedly have been considerably more rapid if fresh soil had been used.

The rapidity with which denitrification occurs can be shown even more strikingly if heavy suspensions of pure cultures of denitrifying bacteria are used. Using the Warburg respiration technique, for example, the author has obtained almost quantitative conversion of nitrite-nitrogen into gas by both actively growing and "resting cells" of *Bacterium denitrificans* and of *Pseudomonas fluorescens* during a period of 2 to 3 hours in the absence of oxygen. Where even a low percentage of oxygen is present, the rate of evolution of nitrous oxide and molecular

nitrogen is usually near zero. For many years it was rather commonly believed that bacterial denitrification occurs only in soils that are completely anaerobic. Several more recent papers (Broadbent, 1951; Broadbent and Stojanovic, 1952; Marshall *et al.*, 1953; Sacks and Barker, 1949; and Wijler and Delwiche, 1954) have, however, generally agreed with some earlier work (Corbet and Wooldridge, 1940; Meiklejohn, 1940) in showing that although the process is markedly inhibited by oxygen, it is not stopped completely. It is not, however, easy to demonstrate nitrogen evolution in soils that are kept well aerated, because the losses are usually too small to measure accurately by ordinary nontracer analytical procedures. Nor is it easy to account for all of the nitrogen added even if tracer techniques are used (MacVicar *et al.*, 1950; Wijler and Delwiche, 1954). This subject needs further investigation.

Bacterial denitrification is brought about by a comparatively few species of aerobic bacteria that are able to grow anaerobically if suitable hydrogen acceptors are present. All of them seem to prefer to use molecular oxygen as the hydrogen acceptor but also have the ability to substitute nitrites, nitrates, and nitrous oxide for it. The extent to which NO compounds can compete with O_2 as hydrogen acceptors seems to vary in some cases with the growth medium and the gaseous atmosphere in which they have grown for several transfers. The work of van Olden (1940) with *Micrococcus denitrificans* illustrates this.

5. *Losses as Organic Substances from Plants*

A few organic substances, such as methylamine, trimethylamine, hydrocyanic acid (Franzke and Hume, 1945), and nicotine are known to be exuded from plants, and a portion of these compounds may be lost by volatilization. Nitrates, nitrites, and ammonia also commonly occur (Wilson, 1943) in plant exudates, but very likely most of this nitrogen returns to the soil. Data on the quantities of nitrogen lost to the air from growing plants, whatever the mechanism of loss, are scarce, but such losses are believed to be meager (Allison *et al.*, 1948; Allison and Sterling, 1948).

6. *Practical Importance*

When consideration is given to the various channels through which nitrogen can be volatilized, it is not surprising that soil nitrogen balance sheets seldom balance. One might almost be tempted to ask why the unaccounted-for figures are not higher than the 15 per cent average value previously mentioned for lysimeters. Under conditions where soils

are likely to be less aerobic than they are in lysimeters, larger losses would certainly be expected. In the presence of nitrates this might occur (1) in rice paddies (Baars, 1950; De and Digar, 1954), (2) in heavy soils that are poorly drained, (3) in normal soils during wet periods, or (4) in normal soils where fresh organic matter is abundant. Large losses would also be expected as a result of the volatilization of ammonia from normal soils where the pH value is 7 or above, and ammonia is added at or near the surface, or being formed at a rapid rate.

In this connection it is of interest to refer again to the dry-land soils of the United States where leaching beyond the 4-foot depth seldom occurs. In such regions, as pointed out above, many of these soils have lost far more nitrogen during the past 50 years than has been removed in the crops. Presumably most of this loss has occurred through volatilization, but positive proof of this is lacking. Since most of these soils are basic, or only slightly acid, the chief loss may be as ammonia. It would be difficult to prove this because the losses have been spread over such a long period of time and have decreased as the nitrogen level of the soil was lowered.

VII. Gains of Nitrogen from the Air by Means Other than Legumes

In the previous discussion emphasis has been placed on the success of the experimenter in accounting for all of the nitrogen originally present in a soil plus that added to it in fertilizers, manures, seed, rainfall, and irrigation waters. It is now well to consider the probable magnitude of the nitrogen gains from the air, which may be occurring at the same time.

So far as the present discussion is concerned, the subject of nitrogen fixation by legumes can be omitted, for their importance in maintaining and increasing soil nitrogen is well appreciated, even if the exact quantity of nitrogen fixed is seldom known. This quantity commonly amounts to 40 to 200 pounds of nitrogen per acre of legumes annually and may be even higher. The plant species, effectiveness of the bacteria used, rainfall, climate, nutrient status of the soil, and weed competition are among the more important factors affecting the quantity of nitrogen fixed.

The chief enigma centers around the question: How important is nonsymbiotic nitrogen fixation in soils? This subject will be discussed and, in addition, a few other possible sources of nitrogen gain will be mentioned.

1. Some Reported Nitrogen Gains under Field Conditions

In the early years of the science of soil microbiology it was determined by many investigators that uncropped soils may sometimes show gains in nitrogen. The isolation of the anaerobic nitrogen-fixing bacterium, *Clostridium pasteurianum*, by Winogradsky in 1895, and of two species of the aerobic *Azotobacter* by Beijerinck in 1901, served to explain, at least partially, these nitrogen gains. An intensive and enthusiastic study of the free-living organisms followed. In the laboratory, where both pure cultures of the bacteria and soils were studied, there was usually no difficulty in demonstrating nitrogen fixation if sugar or other suitable energy sources were supplied. Under field conditions, however, negative results were predominant, and interest in these organisms from the practical standpoint waned. Most of these early workers seemed convinced that in ordinary soils the fixation was too small to be measured accurately, especially under conditions where leaching and gaseous losses of nitrogen were occurring simultaneously.

Many reports of appreciable nitrogen fixation in field plots or lysimeters, usually attributed to nonsymbiotic bacteria, have, however, been reported. Examples of these are the publications of Chapman *et al.* (1949), Hall (1905, 1912), Löhnis (1909), Morse (1936), Smith (1944), and Smith *et al.* (1954). Reports of nitrogen fixation in grasslands (Karraker *et al.* 1950; Lyon and Wilson, 1928; Miller, 1947; Richardson, 1938; White *et al.*, 1945; Whitt, 1941) are especially common, considering the number of such studies made. Numerous reports of fixation have also come from studies in tropical and Far Eastern soils.

How is the reader to evaluate claims of fixations of 20 to 40 and more pounds of nitrogen per acre annually in cultivated and grassland soils in the Temperate Zone? It should be emphasized first that for every positive result there are many, many negative ones. Furthermore, when a large fixation is obtained it is likely to be emphasized, whereas a loss or small gain may scarcely be mentioned. From our knowledge of the physiology of the nonsymbiotic nitrogen-fixing organisms, as well as of the accuracy with which field experiments can be conducted, it would seem that reported nitrogen gains in grassland soils are much more likely to be reliable than are those for cultivated soils. But even nitrogen increases in grass sods that may seem to be real are very likely to be only apparent, for a variety of reasons including: (1) errors of soil sampling and analysis, especially where organic matter accumulations are involved; (2) inadequate allowance for additions of nitrogen in the rainfall; (3) failure to keep the grass free from all legumes; (4)

insufficient protection against the collection of extraneous material, especially due to winds; (5) lack of certainty that nitrogen is not obtained from the subsoil or ground waters; and (6) inadequate replication and lack of statistical treatment of the data. Frequently a grass plot is located along side of a cultivated plot, and the marked difference in nitrogen content after several years is emphasized. Obviously such data furnish no reliable information on the importance of nonsymbiotic fixation if the quantities of nitrogen lost by leaching and volatilization are not known accurately, and they seldom are.

2. *The Organisms Involved*

Another and, it is believed, more accurate way of evaluating the importance of nonsymbiotic nitrogen fixation in soils is to consider the organisms involved and their physiology so far as it relates specifically to nitrogen fixation. The microorganisms of chief importance are the anaerobic butyric acid bacteria, such as *Clostridium;* the aerobes of which *Azotobacter* is the chief representative; and certain blue-green algae, chiefly *Nostoc.*

The anaerobic nitrogen-fixing bacteria are widely distributed in soils and are apparently able to grow, or at least to live, under rather widely varying environmental conditions. Often they are the predominant, or even the only, nitrogen-fixing organisms present, although they are likely to occur chiefly as spores (Swaby, 1939). Some workers have expressed the opinion that the anaerobes are probably of more economic importance than are *Azotobacter,* but present information does not justify definite conclusions on this matter. Although anaerobic, these organisms can grow in soils that are aerobic, possibly owing in part to their association with other species of organisms that are removing oxygen from their immediate environment. So far as their nitrogen-fixing ability is concerned, it has been rather generally agreed that the chief limitation to growth in soils is the small supply of suitable energy sources, and the inefficiency with which they utilize these sources. Normally they convert sugars to organic acids, especially butyric, but cannot utilize the energy in these products. Most workers have obtained less nitrogen fixation per unit of sugar utilized by these anaerobes than by *Azotobacter,* although the fixation per unit of energy utilized may be higher. These long-accepted views have, however, been challenged recently by Parker (1954). He found that when the necessary growth factors were supplied to a liquid medium, *Clostridium butyricum* fixed in 10 days an average (6 analyses) of 27 mg. nitrogen per gram of glucose supplied. Using such an improved medium he also obtained much larger numbers of viable cells in soils than most other investiga-

tors have observed. These newer findings are very interesting, but it is still necessary to know if any appreciable percentage of the cells found in soils occur in other than the spore form. Data are also much needed on the quantities of nitrogen fixed by these anaerobes in soils under normal conditions.

Azotobacter are widely distributed in soils that have a pH value of 6 or above, but not in more acid soils. One strain, *Azotobacter indicum*, will tolerate marked acidity, but this organism has been reported from only a few locations. Although a fairly common soil organism, *Azotobacter* seldom occurs in large numbers. Its energy requirements are high. Under the most ideal conditions, and in experiments lasting less than 24 hours, Wilson and Burris (1953) state that in pure culture fixation of 15 to 20 mg. of nitrogen per gram of sugar is common; the efficiency decreases with age of culture. The organism can utilize only simple energy sources. Crop residues become available only as a result of attack by other organisms that are likely to use most of the food supply themselves. It sometimes cooperates (Imshenetskii and Solntseva, 1940; Jensen and Swaby, 1941; Vartiovaara, 1938) with cellulose-decomposing organisms to obtain its energy supply, but information on this is still rather meager. In the presence of much available nitrogen, or in the absence of an adequate supply of the essential catalytic element molybdenum, the quantity of nitrogen fixed is usually low. Some workers have thought that *Azotobacter* lives in the rhizosphere of higher plants and obtains its energy supply from root excretions, but recent studies (Clark, 1948; Jensen, 1940) have not shown that the organism grows in large numbers in association with roots. Even if they could thrive in this environment, it is not likely that they could obtain much utilizable carbohydrate from the roots.

Many attempts (Allison, 1947; Allison *et al.*, 1947; Bukatsch and Heitzer, 1952; Fåhraeus *et al.*, 1948; Gainey, 1949; Schmidt, 1948–49; Wichtman, 1952) have been made to demonstrate that *Azotobacter* inoculation of soils increases crop production, but nearly all of these attempts, except in the U.S.S.R., have given negative results. Many large increases in yields have been reported from the U.S.S.R., however, and at the present time millions of acres of nonlegumes are being inoculated annually in that country. Apparently Soviet scientists are convinced that such a practice is profitable. There is, however, an increasing tendency for workers in the Soviet Union, and also in Germany, to attribute any benefits obtained to the production of auxins and other plant growth factors rather than to nitrogen fixation. Considerable work (Bukatsch and Heitzer, 1952; Spicher, 1954) is also being done in Germany and in the U.S.S.R. in an attempt to get strains of *Azotobacter* to

adapt themselves to the roots of nonlegumes. There is little indication of success in any of these studies.

A few genera of blue-green algae are able to utilize atmospheric nitrogen if they are grown in a suitable inorganic medium with light as the source of energy. Under some special conditions they are probably of far greater importance as nitrogen gatherers than are free-living bacteria. In an environment such as a rice field, for example, several studies (De, 1936; De and Sulaiman, 1950; Okuda and Yamaguchi, 1952; Singh, 1942; Watanabe, 1950; Watanabe *et al.*, 1951) show that blue-green algae are commonly abundant and active in nitrogen fixation. Although not limited by lack of energy supply if grown in light, they do require much moisture, a neutral medium, and a fairly warm climate. Even under optimum conditions their rate of growth is very much slower than that of bacteria. These facts would indicate that they are not of great importance in normal soils, but quantitative data in support of this viewpoint are lacking.

Much interest is now being manifested in the photosynthetic bacteria which were only recently shown to be able to utilize atmospheric nitrogen. The work to date, which is reviewed by Wilson and Burris (1953), is concerned with the physiology of the organisms and the mechanisms of the fixation process. There is no evidence that these bacteria are of any appreciable importance in soils.

Certain higher nonlegume plants, such as *Alnus* and *Casuarina,* also fix nitrogen just as do legumes, when they are inoculated with the proper organisms and have developed root nodules. Other plants have nodules in the leaves. Most of these plants are trees or shrubs and hence of no importance in general agriculture. Many claims have also been made that various common nonlegume crops can fix nitrogen when they are grown in a deficiency of nitrogen. These claims have not been substantiated and hence need not be considered further in this discussion.

3. *Nonbiological Nitrogen Gains*

Aside from the nitrogen brought down in rainfall, two other suggested sources of soil nitrogen gain by other than biological agencies need to be mentioned. These are nitrogen fixation by sunlight and absorption of ammonia from the air by soils and plants.

Photochemical fixation of nitrogen in soils has been much emphasized in India by various workers, especially Dhar (Dhar, 1946; Dhar and Sheshareharyulu, 1941; Dhar *et al.*, 1941). These workers report comparatively large fixations under laboratory conditions when sterile soil is exposed to light if suitable energy sources are available for oxida-

tion. Until such claims have been verified by workers elsewhere, serious consideration cannot be given to such a nonbiological fixation process, especially in nontropical countries.

Ingham (1940, 1950) was not impressed with the importance of free-living nitrogen-fixing bacteria in soils and suggested that the restoration of nitrogen to soils, commonly attributed to microorganisms, is more likely due to the absorption of ammonia from the air by cellulose and related materials, and by organic and inorganic colloids in the soil. He was of the opinion that the quantity of ammonia so absorbed each year may be adequate for a good growth of many crops. At a much earlier date, Hall and Miller (1911) studied this same phenomenon, using sulfuric acid as the absorbing agent, and concluded that such absorption would be less than a pound of nitrogen per acre per year. If comparatively large quantities of ammonia are constantly being absorbed from the air by living plants, soil humus, and inorganic soil colloids, as Ingham suggests, it is difficult to see why nitrogen should ever be very deficient in any cropped or uncropped soil. Certainly more evidence is required before much importance can be attached to this method of soil nitrogen gain.

4. *Practical Importance—A General Statement*

The above brief review of the chief known facts regarding nitrogen gains from the air through channels other than legumes emphasizes how little actual quantitative information is available that applies to field conditions. There is, of course, little doubt but that nonsymbiotic fixation of nitrogen is of some importance in agriculture, but just how important under various soil and climatic conditions cannot be stated with accuracy. Most workers (Jensen, 1950; Norman, 1946), at least those outside of Russia and India, consider that the quantity of nitrogen fixed in the average soil by free-living organisms is small. The writer is in agreement with this rather generally accepted view. However, it does seem barely possible that as much as 20 pounds per acre of nitrogen may be fixed annually in an occasional well-limed grassland, where conditions are especially favorable for biological activity. Likewise, fixations of this magnitude might possibly occur where very large applications of carbonaceous crop residues are made to certain cultivated soils. Although such nitrogen gains may be possible, there is little justification for a positive statement that they occur. As has been emphasized above, methods do not permit the accurate measurement of such quantities of nitrogen under field conditions. Even if there were no losses of nitrogen through volatilization and leaching, the sampling and analytical errors would be as large or larger in most experiments as the

maximum gains expected. Researches during the past 20 years have not supplied information that would seem to justify any substantial increase in the estimate made by Lipman and Conybeare in 1936 that an average of 6 pounds of nitrogen is fixed per acre per year by nonsymbiotic organisms. This estimate, when made, was based on wholly inadequate data, and any estimate made today would also be little more than a guess. Our present knowledge of nonsymbiotic bacteria might indicate that the 6-pound figure is high. On the other hand, the contribution of blue-green algae, which had barely been discovered in 1936, might be appreciable. Although their main contribution is doubtless in rice paddies and similar locations, it is not unlikely that they may also make some small contribution to the nitrogen supply in nonacid grassland soils and other places where moisture is favorable at certain seasons of the year. In addition, there are good reasons to believe that soils may absorb traces, at least, of ammonia and oxides of nitrogen from the atmosphere.

VIII. Concluding Statement

This evaluation of the pertinent data that relate to soil nitrogen balance sheets has, in general, emphasized the ease with which nitrogen is lost from soils. Mineral nitrogen, whether added as fertilizer or formed from soil organic matter, will not long remain in the soil in this form. If it is not assimilated by higher plants it will usually either be leached from the soil or be lost by volatilization. The extent of loss by leaching depends chiefly upon soil texture and on the amount of rain that penetrates the soil before the crop can assimilate the nitrogen. Leaching losses can be minimized to some extent by providing sufficient carbonaceous materials to combine with it. But this fixing of the nitrogen by carbon is only temporary unless there is a permanent change in the agronomic system that will permit the establishment of a new equilibrium, and a higher organic matter level. Losses by volatilization, which may be large under some conditions described above, can be kept to a minimum by using a few precautions. It is especially important that ammonia either not be applied to alkaline soils or that it be well incorporated with them; otherwise some of it may escape as gas. Bacterial denitrification can be minimized by applying nitrate-nitrogen only at the time the crop is ready to assimilate it. The longer such nitrogen is present in soils, especially if conditions of aeration are not good, the greater the probability of loss as oxides of nitrogen and as free nitrogen gas.

From the facts presented it is obvious that, regardless of years of research, an accurate soil nitrogen balance sheet for a field soil can

seldom be drawn up. This is, of course, because we usually lack quantitative data for some of the major items that are known to be involved in the calculations. The data are lacking because of the experimental difficulties encountered in obtaining them. It is impossible, or at least impractical, to account for all soil gains and losses in a single experiment conducted under reasonably normal growth conditions. In order to obtain accurate values for some sources of gains and losses it is necessary to make the experimental conditions more and more artificial. The experimenter then wonders how closely the data obtained apply under field conditions.

It would seem, however, that the enigma of soil nitrogen balance sheets is much less of an enigma now than it was a few years ago. Enough facts have been established with regard to both losses and gains to permit rather satisfactory explanations for most observed unsatisfactory balances, provided the soil conditions, cropping system, and fertilizer practices used, are known. Although the main mechanisms of loss are probably known, quantitative data relating to each type of loss are certainly inadequate. Even the leaching losses under widely different soil and topographic conditions are not known accurately, and these are far easier to measure quantitatively than are the gaseous losses. On the other side of the balance sheet, there is need for convincing experimental support, established statistically, for the claims of large fixations of nitrogen in tropical soils and in grasslands through channels other than legumes.

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Weed Control in Principal Crops of the Southern United States

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CONTENTS

I. General Nature of Problem

Perhaps in no other area of the United States do weeds limit the production and returns from crops and pastures as in the southern states. Relatively mild winters and high rainfall conditions during the spring planting season favor the development of many species of weeds. Unless satisfactory measures are taken to control the weeds in row crops, and sometimes in cereal crops, such as rice, serious yield reductions or total crop losses occur. In most row crops annual weeds become prevalent almost simultaneously with emergence of the crop seedlings. Rains during the spring months frequently cause prolonged delays in cultural procedures and thus permit unabated establishment and growth of weedy plants. The potential usefulness of satisfactory herbicides to prevent or delay the development of weeds during the wet periods or immediately thereafter, without injuring the crop plant, is obvious.

Weedy species with widely differing growth characteristics infest much cropland of the South, ranging from those inhabiting the semiarid areas of western Texas and Oklahoma to the subtropical areas of lower Florida. Because of the wide range in weed species there are no simple mechanical or chemical control methods universally applicable to the different crops grown in the region. The weed research man is faced not only with a multiplicity of problems as regards crop-weed relationships, but also with soil and climatic variables which add complications to the development of suitable weed control programs. Great diversity in acreage devoted to a given crop between farms imposes limitations on research directed toward developing equipment and methods suitable for both large and small production units.

It is not possible within the scope of this article to treat all the various weed problems and the advances made in their solution by using cultural and chemical methods. Attention is given primarily to the weed problems on which most progress has been made, with emphasis placed on usage of herbicides. Selection and satisfactory employment of an herbicide to control a specific weed is dependent largely on the crop involved, and therefore the subject has been subdivided by crops.

II. Cotton

1. *Nature of Problem*

In the humid portion of the Cotton Belt annual weeds such as crab grass (*Digitaria sanguinalis* (L.) Scop.), pigweed (*Amaranthus* spp.), morning-glory (*Ipomoea purpurea* (L.) Roth), and *Brachiaria* spp. commonly germinate and emerge concurrently with cotton seedlings. For generations the removal of these annual weeds has been done by cultivation and hand hoeing. Mechanical methods are not dependable because field operations are frequently interrupted by rains, and in addition no completely satisfactory machine method of removing weeds growing intimately with small cotton has been devised. Consequently in the absence of other methods hand hoeing is a necessity. Removing weeds from cotton by hoeing is a high-cost item of production, averaging between $15 and $20 per acre annually. Failure to eliminate weeds results in lower yields and quality, and inevitably in reduced dollar return per acre. Wide fluctuation in availability of labor for hoeing and picking cotton has stimulated research effort completely to mechanize production of this crop. Weed control is now one of the last, most expensive, and most complex gaps to be completed in cotton mechanization. Within the last five years considerable progress has been made in developing combination chemical and improved cultural practices to reduce substantially the hand labor requirements and costs of producing cotton.

2. *Cultural Weed Control Methods*

Until large-scale use of the tractor became a reality in the Cotton Belt, tillage implements were those commonly used for several decades on mule-drawn cultivators and consisted of a varied assortment of shovels and sweeps. Within the last few years improved implements and methods of using them have aided materially in reducing hand labor requirements.

a. Rotary Hoe. During the last several years the rotary hoe has been an effective and economical tool in the production of cotton. It

is rather widely used throughout the Cotton Belt and is especially useful in the less humid portion of the rain-grown cotton area. It is used not only for controlling weed seedlings but also for breaking crusted soil and thereby promoting the emergence of cotton following soil-packing rains. Usually the first rotary weeder cultivation is made 3 or 4 days after the cotton plants have emerged or earlier if a hard crust has formed. Subsequently, the rotary hoeing is done weekly for about three weeks. Employment of the rotary hoe after emergence of the crop requires that there be proper stands because about 15 to 25 per cent of the cotton plants may be eliminated during a season (Westmoreland *et al.*, 1954). In addition uniform seedbeds are desirable for most efficient use (see Section II, *3a*). Speed of operation varies with individual conditions, but commonly speeds of 5 to 8 m.p.h. are used. Speeds up to 18 m.p.h. have been reported where pull-type implements were employed (Rea, 1954a).

The chief disadvantages of the rotary hoe are that (1) it fails to control weeds under wet conditions when the need is most critical, (2) it is impractical to use when the initial crop stand is minimal, and (3) small weeds adjacent to cotton plants do escape control, become established, and require meticulous hand hoeing for removal.

b. Cross-Plowing. Check-rowing or cross-plowing of cotton in the Mississippi Delta area was practiced to some extent following the flood of 1927 (Meek and Williamson, 1952). Difficulty was experienced in check-planting of cotton because of unavailability of suitable equipment. Accordingly, the practice of cross-plowing was introduced and has grown in popularity on certain of the flat cotton plantations of the Mid-South. Meek and Williamson emphasized that where cross-plowing is practiced cotton must be drilled to obtain a thick stand so that the hill of plants left is short and compact (*ca.* 6 to 18 plants). Disk hillers on the front cultivator shanks followed by sweeps have been found more satisfactory in establishing hills uniformly spaced than sweeps alone. Cross-plowing normally reduces materially the amount of hoeing required for weed control and has shown particular promise for keeping Johnson grass under control. Cross-cultivation is highly compatible with flame cultivation to control late-season weeds (see Section II, *3c (3)*). In studies conducted over the period 1944 to 1950 Meek and Williamson (1952) found that the average yield of seed cotton from drilled and cross-plowed cotton was approximately the same, and the man-hours of labor required for chopping and hoeing of weeds were reduced substantially.

The disadvantages of cross-plowing are (1) more seed are required per acre, (2) erosion problems are created in many fields, (3) mechani-

cal picker efficiency is reduced significantly, and (4) annual weeds sometimes infest the hills, and their removal by hoeing may be damaging to cotton if not done early enough.

c. Sweep Cultivation. The equipment for sweep cultivation of cotton is similar throughout the Cotton Belt. Shallow cultivation is emphasized to minimize root pruning and to avoid throwing too much soil into the drill area, which may interfere with subsequent application of chemicals or flame and also with mechanical picking. The proper employment of the newer types of sweeps for tractor cultivators does an excellent job of keeping the middles free of weeds and maintaining a proper seedbed for subsequent weed control practices and mechanical harvesting. Accuracy of setting the sweeps has been stressed and devices to aid in proper adjustment have been described (Meek and Ewing, 1948).

3. *Chemical Control in Combination with Cultural Practices*

Leonard *et al.* (1947) reported the results of preliminary studies in Mississippi on the use of dinitro compounds as pre-emergence herbicides for cotton. These workers suggested the possibility of using herbicides on only a 12-inch band centered on top of the row; this was made with a view to reduce cost per acre of the chemical and at the same time reduce or eliminate hand hoeing. Between 1948 and 1950 considerable work in Mississippi and Louisiana demonstrated the feasibility of using special herbicidal oils as directed sprays to control small weeds in growing cotton. Davis and Talley (1950) and Cowart *et al.* (1950) reported highly satisfactory weed control without crop damage from using a combination of ammonium 4,6-dinitro-*o*-secondary butyl phenate as a pre-emergence treatment and post-emergence oil applications to control weeds escaping the earlier treatment. Thus began research on materials and problems centered around the chemical control of weeds on the top of the cotton row and cultural control of weeds in the middles between the rows.

a. Residue Removal and Land Preparation. Earliest studies with pre-emergence and post-emergence herbicides showed that success was dependent upon certain preplanting operations and in particular the preparation of a proper seedbed (Cowart *et al.*, 1950). Crop and weed residues and clods of soil on the surface of the seedbeds were found to reduce the effectiveness of the pre-emergence herbicide and to hinder the subsequent lateral application of the herbicidal oils. Accordingly, much stress has been given to proper disposal of plant residues in preparing cotton fields for herbicidal usage. Creasy *et al.* (1951) emphasized that the degree of success achieved in the use of chemicals for

weed control in cotton is largely dependent on the care exercised to assure proper application. Seedbeds should be thoroughly prepared and uniform in height and width. Planting and other operations preceding the first herbicide application should be such that the resulting seedbed is 3 to 4 inches higher than the middles, with the top of the row as flat as possible for a width of 12 to 14 inches. Such conditions are deemed favorable to efficient applications of herbicides and terminal treatments with flame (see Section II, *3c (3)*). Firmness and smoothness of the seedbeds are highly important to insure not only prompt crop emergence but also uniform coverage of the soil surface with an herbicidal spray.

b. Pre-Emergence Treatments. Proper and efficient application of pre-emergence herbicides dictated that new equipment or modifications in bed equipment be made in order that bands of herbicide could be placed over the row to eliminate or reduce substantially the weeds in the drill or the area where they are not controlled readily by mechanical means.

(1) Equipment devices and planting. Single flat-fan nozzles directly behind the planter presswheel are used to spray bands 12 to 14 inches wide, thus reducing materially the cost of treatment per acre in comparison to the more common broadcast spraying employed for controlling weeds in cereals, range lands, and pastures. In addition by combining the herbicide application with planting, correct placement of the spray is insured and one operation is eliminated. Special rollers 12 to 14 inches wide substituted for the conventional planter presswheel or drawn behind the planter wheel (Fig. 1) have been found useful for increasing the smoothness and firmness of seedbeds, especially on seedbeds tending to be cloddy. With the introduction of herbicides absorbed and translocated by the roots of weeds, the usage of rollers on firm, well-prepared seedbeds does not appear to be important in promoting weed control, particularly if rains occur prior to crop and weed emergence. Intensive studies are under way to re-evaluate the usefulness of rollers under different conditions and with different pre-emergence substances.

For best results cotton should be planted in hills and at such a rate that no thinning of the plants is required. Newer planters and experimental ones do satisfactory hill dropping. One of the shortcomings of multiple-row planters has been some irregularity in depth of planting due to incorrect adjustment or unevenness of seedbeds; this increases the likelihood of herbicide damage to shallow planted seeds. With properly adjusted equipment operating on seedbeds of uniform height and width, excellent planting can be done for chemical weed control.

Disturbance of treated soil surfaces permits weed seeds deeper in the soil to germinate. Consequently, it is necessary to avoid mechanical thinning or chopping of cotton. Furthermore, with efficient use of pre- and post-emergence herbicides and flame, a band area centered on top of the row (Fig. 2) is not disturbed from planting to harvest.

Numerous herbicides have been tested as pre-emergence treatments for cotton. Currently, the most promising ones include one or more of

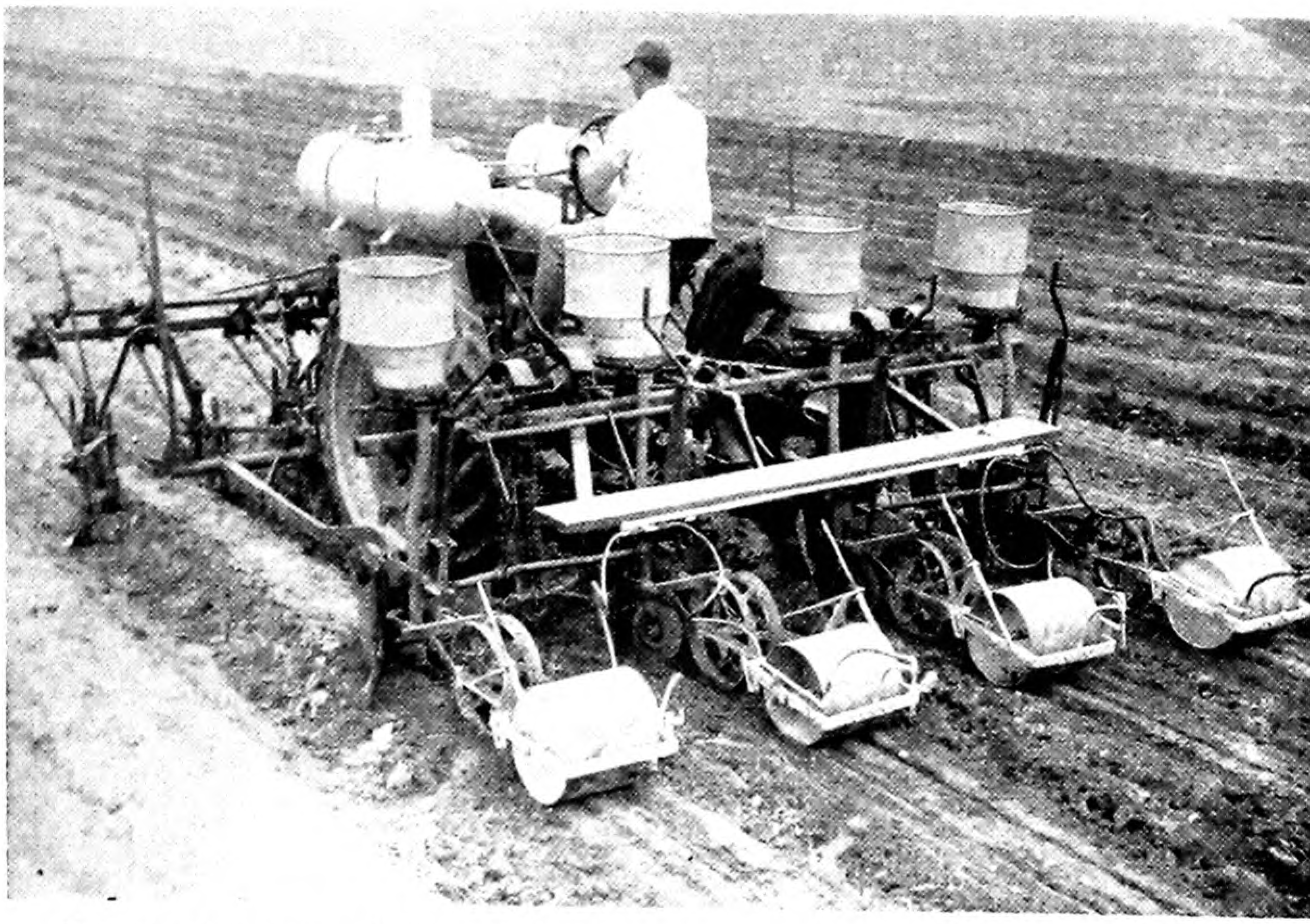

FIG. 1. Four-row planter equipped with special rollers to smooth seedbeds of cotton prior to application of pre-emergence herbicides. (Courtesy Delta Branch Mississippi Experiment Station.)

the dinitros, carbamates, or ureas. Space limitations dictate discussion of only the materials farmers have used or those under intensive study.

(2) *Dinitros.* Certain of the dinitro compounds and pentachlorophenol (PCP) were the first herbicides that showed promise for pre-emergence use in cotton (Leonard *et al.*, 1947; Cowart *et al.*, 1949). These materials cause injury or death of plants by contact; little or no translocation occurs (Barrons, 1950). Some of the principles and techniques employed with translocatable and systemic pre-emergence materials today as regards volume of spray, seedbed preparation, etc., were based on early observations made with the contact-type herbicides.

The dinitros most commonly used have been the alkanolamine salts

or triethanolamine salt of 4,6-dinitro-ortho-secondary butyl phenol (DNBP), although in some of the early work the oil-soluble form of the compound was tested intensively. Because of its higher cost and lack of displaying a consistent advantage over the water-soluble forms of DNBP, little or none of the oil-soluble material has been used by farmers.

The safety with which DNBP can be used as a pre-emergence herbicide for cotton varies with soil characteristics. Generally for sandy

FIG. 2. Cotton field in the Mississippi Delta showing outstanding weed control following excellent jobs of seedbed preparation, pre-emergence band application of CIPC, and post-emergence middle cultivation.

loam soils application rates of 5 to 8 pounds per acre are considered satisfactory, whereas on clay loam and mixed bottomland soils rates of 8 to 12 pounds per acre have given good results. Except on the clay loam soils heavy rains following application of DNBP tend to leach the material downward to the germinating seed and frequently cause crop stand reduction. The dilution of the herbicide by leaching also decreases its effectiveness in controlling weeds. Under moderate to light rainfall conditions between planting and crop emergence DNBP usually gives excellent control of broadleaf weeds such as *Amaranthus* spp. and good control of the troublesome annual grasses including *Digitaria* spp.

In the absence of rainfall for several days after treatment poor weed control can usually be expected.

During the 1952 cotton planting season the herbicide DNBP was responsible for the loss of stands on many farms in the Mississippi Delta areas. The damage occurred during abnormally high temperatures for the time of year. Subsequent studies have elucidated the factors deemed important to an understanding of the phenomenon.

High temperatures and little or no rainfall following the pre-emergence application of DNBP have been shown to be conducive to the water vapor distillation of the compound (Hollingsworth and Ennis, 1953; Barrons *et al.*, 1953). The latter workers showed that water vapor escaping from soil surfaces upon which DNBP rests carries the phenol along with the water vapor in proportion to the amount of water vaporized. Hollingsworth and Ennis (1953) found that vapor injury to cotton from DNBP was influenced by (1) the amount of soil moisture present, (2) temperature, and (3) the age of the plants. They found that vapor injury to cotton was small at temperatures of 70° to 84° F., but above 90° F. the vapors killed a high percentage of young cotton plants. These findings were corroborated in independent studies by Linder *et al.* (1953). At soil moistures of 0 to 5 per cent the DNBP vaporization was small, but at the same temperatures vapors from soils containing 11 and 17 per cent moisture were highly toxic to cotton (Hollingsworth and Ennis, 1953). Barrons *et al.* (1953) discovered that the addition of lime reduced phenol transfer by water vapor and explained that the high concentration of calcium ions in a thin zone pushed the nitrophenol salt equilibrium towards the calcium salt, which is not water-distillable. They suggested the use of calcium carbonate applied as a tank mix or lime dust just ahead of the sprayer as a means of preventing DNBP vapor injury to cotton. Subsequent work by Hollingsworth (1954) showed that vapor injury from DNBP applied to soils with a pH of 7.3 or above was negligible, but under the same conditions sufficient vapors were produced from a soil with a pH of 5.5 to cause death of cotton seedlings. The addition of 50 pounds per acre of lime as a spray immediately after treatment was shown to minimize DNBP vapor injury under greenhouse conditions. These findings have been corroborated by other studies (Davis *et al.*, 1954; Davis and Davis, 1954).

In lysimeter tanks the distributions of both water-soluble and oil-soluble DNBP following different amounts of simulated rainfall have been studied (Davis *et al.*, 1954). They found that (1) the larger the amount of water added, the greater was the downward movement of DNBP in soils, (2) the DNBP was leached somewhat more in a Norfolk

sandy loam than in a Deer Creek silt loam, and (3) the water-soluble DNBP was moved downward more than the oil-soluble form of the compound.

Davis and Davis (1954) studied the effect of rainfall on the vapor and contact injury of DNBP to young cotton plants under high temperature conditions. These workers report that 0.5 inch of rain falling within a few hours after planting may move sufficient herbicide downward to the seed to decrease cotton stands, but the same amount of rain occurring for the first time after the cotton has germinated and prior to emergence from the soil lessens danger of vapor burn by decreasing the concentration of the material on the soil surface. In contrast 0.5 inch of rain applied 3 to 4 days after emergence of cotton seedlings was described as enhancing vapor injury to the plants. The effects of higher and lower amounts of rain were not reported.

In light of the information produced by studies conducted in 1952 and 1953 it appears that the usefulness of DNBP as a pre-emergence herbicide for cotton will be limited owing to its vapor hazard at high temperatures and also to its inconsistent performance on different soils following rainfall. This statement is borne out by the trend in acreages treated with DNBP between 1950 and 1954. Acreages treated are estimated as follows: 1950, 1200 acres; 1951, 30,000 acres; 1952, 195,000 acres; 1953, 81,000 acres; and 1954, 15,000 acres.

(3) *Carbamates.* Following the reports of Ennis (1949) and DeRose (1951) on the herbicidal properties of isopropyl *N*-3-chlorophenyl carbamate (CIPC) there developed increased interest in carbamates as herbicides for use in crops. DeRose (1951) demonstrated the inhibitory action of CIPC on crab grass (*Digitaria* spp.) growing in pots of cotton. He found CIPC more inhibitory to crab grass than isopropyl *N*-phenyl carbamate (IPC). Leonard *et al.* (1952) described similar observations in field plot studies on cotton conducted in 1950. Because crab grass is probably the most important weed in cotton much work has been done to determine the practicability of using CIPC as an herbicide for cotton. Generally good weed control was obtained in 1951 with CIPC in several of the southern states, and no significant damage to the crop was reported. Usage has increased annually since the material was first introduced, with the exception of 1954, when governmental restrictions on cotton acreages are believed to have discouraged expanded use. Estimated cotton acreages treated with CIPC are as follows: 1951, 16,000 acres; 1952, 60,000 acres; 1953, 180,000 acres; and 1954, 150,000 acres.

Cotton appears to tolerate a rather wide range of dosages of CIPC when applied as pre-emergence spray to most soils. Effective rates of application vary from 5 to 12 pounds per acre, with the lower rates

being used on sandy loam soils and the higher amounts on the clay loams. Field observations have indicated that CIPC is more inhibitory to cotton under cool, wet conditions than under situations favorable to rapid emergence and growth of cotton. There is no conclusive evidence that the differing responses of cotton to CIPC are due to a greater loss of the herbicide during warm weather as compared to cool weather or to a greater inhibitory activity on cotton at low than at higher temperatures (see following paragraph). Both CIPC and DNBP have commonly been applied in volumes of 40 gallons water per acre on a broadcast basis. Four years of experimentation by Ennis (1955) indicate that the effectiveness of CIPC is not reduced by lowering the spray volume to 20 gallons per acre.

CIPC is highly effective in controlling crab grass when some rain occurs between time of planting and emergence of the crop and weeds (Fig. 2). In the absence of any rain for prolonged periods following application usually little benefit is obtained from CIPC. CIPC gives some control of pigweed and certain other small-seeded broadleaf weeds, with ragweed (*Ambrosia* spp.) being a notable exception.

Sufficient studies of the behavior of CIPC in soils have been made to show that its usefulness as a selective herbicide on cotton is dependent to a large extent upon its resistance to leaching in soil (Smith and Ennis, 1953). With moderate rainfall these workers found that the material was localized largely within the top ½ inch of soil and that it was less subject to leaching than 2,4-dichlorophenoxyacetic acid (2,4-D). On porous soils, such as those with high sand content, Blouch and Fults (1953) reported that the dosage levels of CIPC must be reduced greatly or crop injury may occur. Since the selective action of CIPC is due in part to a lack of downward movement, the depth of planting the crop is highly important; cotton plants produced from seeds ¼ inch deep may be severely inhibited by CIPC, whereas those ¾ to 1 inch deep would be uninjured. Although cotton has considerable tolerance to CIPC, this is not great enough to permit the indiscriminate usage of CIPC on cotton under all conditions. Field and laboratory experiments have shown that CIPC at a concentration of 1 p.p.m. is highly inhibitory to cotton seedlings (Snyder, 1953). Swanson *et al.* (1953) have shown that CIPC markedly inhibits root elongation in cotton and depresses respiration with increasing dosages. Accordingly, the material is not recommended for use on soils where downward movement is likely to be excessive; the dosages employed on all soils are gauged to the general characteristics of the soil.

Laboratory studies by Anderson *et al.* (1952) and Linder *et al.* (1954) have demonstrated that much CIPC may be dissipated by vola-

tilization. Pray and Witman (1953) examined samples of soil taken from a field in South Carolina 19 days after treatment with CIPC. A total of 1.68 inch rain occurred between 4 and 7 days after treatment; maximal temperatures ranged between 65° to 96° F. and minimal temperatures, between 49° to 60° F. These workers found that all CIPC occurred within the top 2 inches of soil and over 90 per cent was in the top 1 inch. They were able to recover only 10 to 36 per cent of the initial CIPC applied. Thus a high loss of CIPC occurred under these conditions. It was not determined whether the disappearance was due to volatilization or biological decomposition or both. Work by DeRose (1951) and Aldrich (1953) and others has demonstrated that CIPC disappears from soil. Unpublished evidence obtained by A. S. Newman shows that certain microorganisms are capable of decomposing the material. Following application at rates normally used in cotton Holstun and McWhorter (1953) reported that sufficient CIPC persisted for five months in a sandy loam soil under field conditions at Stoneville, Mississippi, to inhibit oats and soybeans, but little or no responses in these crops were induced after 11 months.

Under the humid and warm conditions of the South the amount of CIPC remaining in the soil after use to control weeds in cotton does not appear to present a hazard to succeeding crops. The too-rapid loss of the material under high-temperature conditions, either by volatilization or microbial breakdown, is sometimes disadvantageous because its herbicidal effectiveness is correspondingly reduced. Several new carbamates are being studied intensively to determine their potential usefulness as pre-emergence herbicides for cotton. Some of them are more stable under high temperatures than CIPC (Linder *et al.*, 1954). Unpublished data indicate that other carbamates are even less subject to downward movement than CIPC. These materials would be improvements over CIPC in that they could be used more safely on a wider range of soils and under more varying temperatures and rainfall than CIPC.

(*4*) *Ureas.* During 1951 the herbicide 3-(*p*-chlorophenyl)-1,1-dimethyl urea (CMU) was introduced (Bucha and Todd, 1951) and tested at several locations in the Cotton Belt as a pre-emergence herbicide for cotton. The material exhibited unusual potency in controlling annual weeds, both grasses and broadleaf, at dosages much lower than necessary with DNBP and CIPC. Investigators have found that the urea is not unlike DNBP and CIPC in that the safety with which it can be used on cotton is influenced by soil characteristics and rainfall. The range in dosage to obtain weed control and to avoid crop injury is narrow, i.e., between 1 and 2 pounds per acre for most soils.

In studies at St. Joseph, Louisiana, in 1951 Normand *et al.* (1952) reported that there was no adverse effect upon yield from CMU applied at rates of 1 to 2 pounds per acre and that the weed control accomplished exceeded that of DNBP at 6 and 8 pounds per acre. Hagood (1952) stated that CMU applied at 2 pounds per acre was generally more effective in controlling weeds than CIPC at 8 pounds per acre, but in the following season the materials were about equally effective at the afore-mentioned dosages (Hagood and Hodges, 1953). Holstun and McWhorter (1953) pointed out that CMU performed similarly to DNBP and CIPC in the absence of rainfall prior to the development of seedling weeds in that the weed control obtained was inconsistent, whereas when moderate rain followed treatment and temperature was favorable for cotton growth all three herbicides promoted outstanding weed control. Under droughty conditions Livingston (1953) observed stunting and chlorosis of cotton in the lower Rio Grande Valley following pre-emergence treatment with CMU, but reported no harmful effects under adequate moisture conditions. Thompson *et al.* (1954) found the weed control obtained with CMU satisfactory on five major soils of Georgia, but unsatisfactory on the sandy soils of the coastal plains area. Other workers have obtained good weed control by CMU applications under most conditions (Albert and Anderson, 1954; Rea, 1954b; Williams and Hinkle, 1953a).

It is known that CMU when applied at high rates, persists in the soil for extended periods, and this property makes it an excellent material for devegetating an area. This property of persistence has caused some concern to investigators studying the material as a pre-emergence herbicide. Holstun and McWhorter (1953) reported that sufficient CMU was present in soil eight months after application to be toxic to oats and soybeans. In contrast, Loustalot *et al.* (1953) found that soil remained toxic to corn and velvet bean four months following treatment at 5 pounds per acre and was injurious to velvet bean only two weeks after application at 1 pound per acre. Under field conditions in Puerto Rico, CMU applied at rates of 1 to 5 pounds per acre apparently does not present a serious residual problem. These workers state that the factors generally favoring soil microbial action seemed also to favor the disappearance of CMU in the soil. They also found that sandy soils retained the CMU toxicity longer than soils with a higher clay content. Much additional information is needed on the residual aspects of this material under a wide variety of soil and climatic conditions before large-scale use on cropland is appropriate.

CMU has presented problems in usage because (1) crop injury may occur on some soils at rates of CMU application considered optimum

for controlling weeds, (2) uniform spraying of the wettable powder formulation from conventional spray rigs is difficult, and (3) overdosage in application is hazardous to cotton. Additional substituted ureas in liquid and wettable powder formulations were released to investigators for evaluation during 1953 and 1954. Primary emphasis was given to 3-(3,4-dichlorophenyl)-1,1-dimethyl urea, 1-(3,4-dichlorophenyl)-3-methyl urea, 3-(phenyl)-1,1-dimethylurea, and 3-(*p*-chlorophenyl)-1,1-dimethyl urea (CMU).

Weed *et al.* (1954) presented a summary of a large amount of data collected throughout the Cotton Belt in which CMU and 3-(3,4-dichlorophenyl)-1,1-dimethyl urea were compared at different dosages as agents for controlling weeds in cotton. These workers concluded from their data that the latter urea was slightly safer than CMU for use on cotton. Evidence was presented by these workers to indicate that the dichloro urea and CMU are reduced to innocuous concentrations in soil within 4 to 12 months after initial application at rates of 1, 2, or 4 pounds per acre. In addition their results indicated that soil microbes aid in the inactivation of both CMU and the dichloro urea. Studies by Hollingsworth (1954) showed that 3-(3,4-dichlorophenyl)-1,1-dimethyl urea was slightly more stable in a soil than CMU, whereas 3-phenyl-1,1-dimethyl urea was less persistent in the soil than either. Unpublished work by Harris in Mississippi has shown that 3-(3,4-dichlorophenyl)-1,1-dimethyl urea caused injury to cotton on soils low in organic matter (0.7 per cent) and with a low pH (4.6) but caused little or no injury on soils with 1 per cent organic matter and a pH above 5.2.

Rea (1954b) found that 3-phenyl-1,1-dimethyl urea induced more conspicuous herbicide symptoms in cotton than CMU and 3-(3,4-dichlorophenyl)-1,1-dimethyl urea at equivalent rates, and also reduced the yield of cotton. Other workers have reported similar results. In general, the compound 1-(3,4-dichlorophenyl)-3-methyl urea has exhibited lower herbicidal activity on a weight basis than CMU and 3-(3,4-dichlorophenyl)-1,1-dimethyl urea (Hollingsworth, 1954).

(5) *Problems needing more work.* A complexity of problems has been created in attempts to employ pre-emergence herbicides on cotton under the wide range of soil and environmental conditions characteristic of the rain-grown portion of the Cotton Belt. Experimentation to date has clearly shown that herbicides act differently on various soils as regards the response of both crop and weeds. The problem is further confounded when variable rainfall and temperature conditions are superimposed. Certain of the newer herbicides and in particular, the ureas, need to be studied carefully as regards the factors influencing their movement pattern and persistence in different soils. More basic

information is required on the behavior of herbicides under different environments. The conditions under which pre-emergence herbicides perform satisfactorily and unsatisfactorily must be fully known. Moreover, the mechanisms of herbicidal actions should be better understood in order to use many chemicals on the soundest bases.

c. Post-Emergence Treatments. (*1*) *Oils.* Early work with herbicides indicated need for pre-emergence materials capable of accomplishing weed control for eight to ten weeks, or for herbicidal substances to apply after crop emergence to extend the period of weed control. Investigations by Talley and Porter (1950), Leonard and Harris (1950), Talley (1950), and Cowart *et al.* (1950) demonstrated the potential usefulness of certain herbicidal oils as precision-directed sprays for controlling young weeds in growing cotton.

Talley *et al.* (1950) tested over 200 petroleum fractions having different boiling ranges, aromatics, naphthenes, and saturated aliphatic compounds, to determine the compositions most suitable for selective weeding of cotton. They found that a naphtha with 24 per cent aromatics was more selective than one containing 16 or 32 per cent aromatics. Leonard and Harris (1950) attempted to determine the relationship between the structure of aromatic and aliphatic hydrocarbon compounds and their toxicity to nut grass (*Cyperus rotundus* L.), Johnson grass (*S. halepense* (L.) Pers.), and soybean. They found that toxicity increased as the number of methyl, ethyl, or isopropyl groups attached to a benzene ring was increased. Benzene, toluene, xylene, trimethylbenzene, tetramethyl benzene, and pentamethyl benzene increased toxicity in the order listed. In a later report these workers (Leonard and Harris, 1952) stated that olefins were more injurious to cotton hypocotyls and grasses than paraffins. The rapidity with which injury developed was found to decrease as the length of carbon chains increased from 6 to 14 carbon atoms. Subsequent work has indicated that oils with the following specifications are satisfactory herbicidal oils for cotton weed control: boiling range between 300° and 400° F., about 24 per cent aromatics, no more than 30 per cent naphthenes, and less than 2 per cent olefins or diolefins (Edwards *et al.*, 1952). Owing to the directional precision required in applying oil sprays to avoid contact with the foliage, much effort has been given to developing suitable equipment. Talley and Porter (1950) described a parallel-action spray shoe developed cooperatively with engineers at the Delta Branch Mississippi Experiment Station. This device had the basic features necessary for applying the oils as directional sprays with tractors. Subsequently, various improvements in the oil spray applicators have been made (Fig. 3), and studies on various angles of spraying oils have pro-

duced information which has increased the efficiency of spraying (Holstun, 1952).

Emphasis has been given to keeping the oil on the lowest inch of the cotton stem, because oil applied high on the stem, on the bud, or on the leaves will injure or kill young cotton plants. Most recommendations for using herbicidal oils indicate that when cotton seedlings are about 3 inches tall the first application of a suitable oil may be made, if needed. Rates of from 5 to 7 gallons per acre on a row basis are considered safe and give excellent control of weeds 1 inch or less in height. Three weeks after emergence of the cotton or after one application no

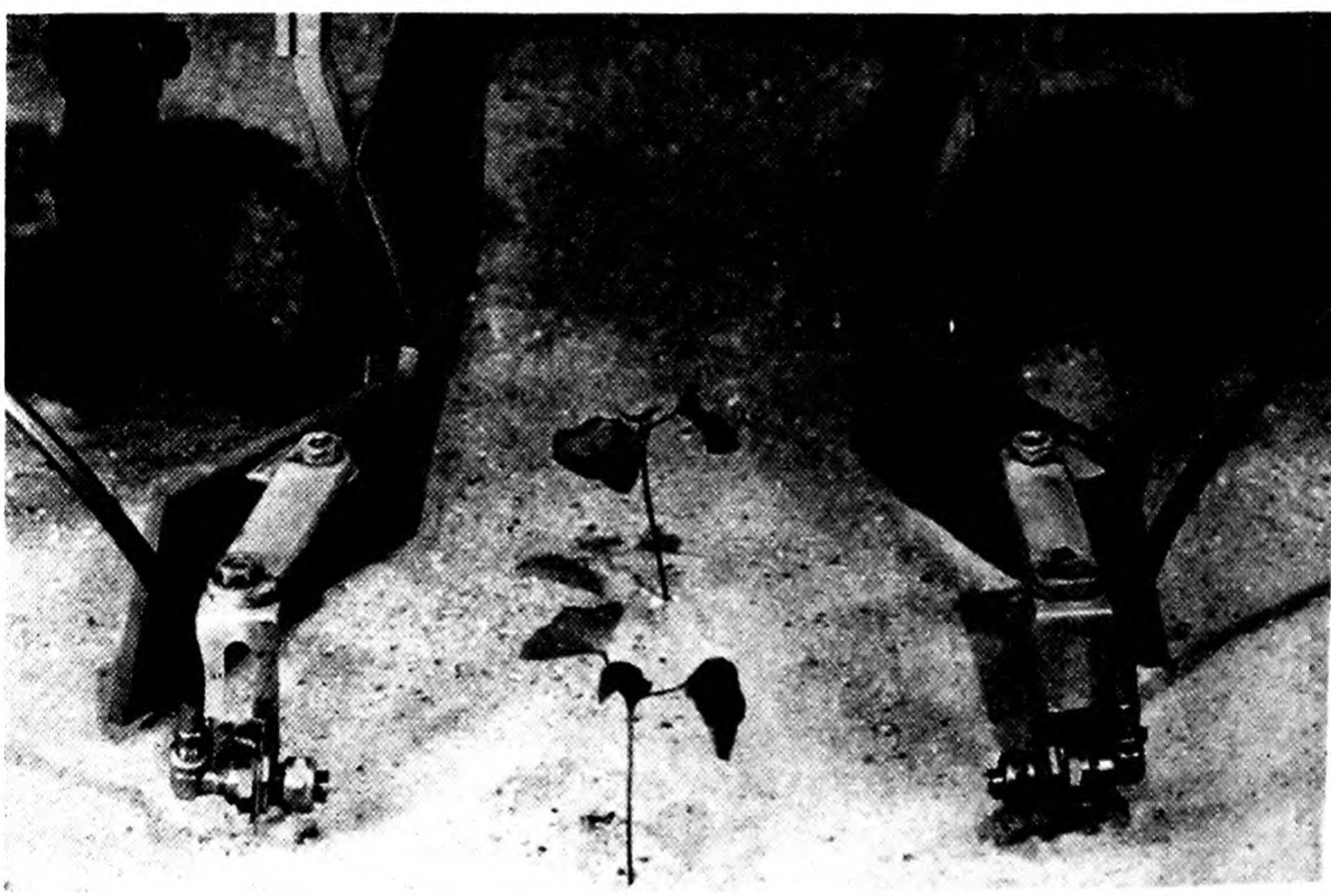

FIG. 3. Applicator for making post-emergence oil treatments to cotton in same operation middles are cultivated with tractor equipment. (Courtesy Delta Branch Mississippi Experiment Station.)

more than 5 gallons per acre is suggested (Edwards *et al.*, 1953). Generally, no more than three applications of oil, spaced at least 5 days apart, are recommended for use on cotton; oil should not be applied after small cracks appear in the lower stem of cotton.

The tolerance of the hypocotyls of young cotton plants to moderate dosages of herbicidal oils has been ascribed to the protection afforded by a waxy cuticle (Ratcliff *et al.*, 1951). These workers also postulated that the decreased tolerance of cotton stems to herbicidal oils coincident with the development of bark cracks could be attributed to loss of cuticle and epidermal cells and to the formation of a more absorbent cork tissue which was presumed to permit oil penetration. Palmer and Ennis (1953) presented data to show that the tolerance of the lower stem of

the cotton plant to a directed spray of an herbicidal oil decreased during the period of transition from a waxy cuticle to the formation of a corky bark. Later they presented histological evidence to show that an unbroken epidermis of young hypocotyls protects the vital tissues from oil damage (Palmer and Ennis, 1954). Superficial cork cracks form in the hypocotyl of plants, as a result of the growth of the vascular cambium and cork cambium and the expansion of cortical parenchyma, and permit oil to move intercellularly to susceptible tissues. These workers found that old hypocotyls had many unbroken cork layers which prevented oil from reaching vital tissues even though superficial bark cracks were present. The oil injury to susceptible cotton plants may be increased by factors, such as high soil moisture, which promote rapid plant growth.

On the basis of the volumes of oil distributed by two companies the cotton acreage treated twice or more with herbicidal oil for post-emergence weed control has increased from about 6000 acres in 1950 to 50,000 to 60,000 acres in 1954. The acreage would probably have increased more markedly if the use of oil did not have certain limitations. The application of herbicidal oils to cotton is a precision operation. Equipment must be calibrated and adjusted accurately to ensure control of weeds without damage to the crop. Uniformity and smoothness of seedbeds are also prerequisites to good jobs of oil application (see Section II, 3*a*). Timing of oil applications to coincide with susceptible stages of weedy growth is necessary, and the weeds must be small or the oils fail to control them. A serious limitation in the use of oils alone to control weeds is the occurrence of rainy days that prevent field operations, with the result weeds grow too large before treatments can be made.

(2) *Residual-type herbicides.* Considerable work is in progress to employ residual-type post-emergence substances instead of oils to control weeds, with a view to reducing the number of applications sometimes required with oils and to extend weed control until harvest.

The same herbicides found useful as pre-emergence herbicides for cotton are showing some good prospects as post-emergence directed sprays. They do not appear to kill the young weeds growing in the drill as effectively and consistently as the contact oils. The action of residual-type materials on weeds germinating after treatment is governed by environmental influences such as high temperature and absence of rainfall for a few days to extended periods after treatment, which decreases their efficiency. The development of new herbicides and application techniques may promote wide usage of residual-type herbicides, especially in areas where late-season weeds are serious problems. According

to a recent report by Arle and Everson (1954) the new urea herbicides are showing promise for controlling late-season weeds in irrigated cotton of the Southwest, but some hazard to succeeding crops is being encountered.

(3) *Flaming.* Neely and Brain (1944) described the efforts made during the period 1935 to 1944 to develop a mechanical device for killing weeds in cultivated crops with flame. The principle of the process was described as being based upon the adjustment of a hot air-blast flame drawn by a tractor along rows of crops so that the weeds were killed selectively with little damage to the crop plants. These workers reported highly encouraging results from their work with a cumbersome diesel fuel machine, the first flaming cultivators used on cotton.

Improvements and simplifications were made in the flame cultivators during the war years, and in 1947 flame cultivators were practically all tractor-mounted and used liquefied petroleum gases—propane or butane—as fuel (Danielson and Crowe, 1948). These latter workers reported that cotton plants must be about 8 inches tall and have stems at least $\frac{3}{16}$ inch in diameter at the soil level before they can withstand the intense flaming heat. Consequently, flame cultivation cannot be depended upon to control weeds developing between emergence of the crop and the time the cotton is large enough to withstand flaming. In addition, large grasses and broadleaf weeds are not readily controlled by flaming. Danielson and Crowe (1948) pointed out that flame cultivation was not the full solution to problems of weed control in cotton production. Notwithstanding, with the advent of pre- and post-emergence herbicides to control early-season weeds and additional improvements in flaming equipment (Fig. 4), flame cultivation, properly used, has proved a valuable and efficient practice for controlling mid-season weeds in cotton. Most weed control recommendations suggest that flaming be used as terminal treatments following pre-emergence and post-emergence herbicides.

d. Economics of Weed Control in Cotton. Crowe and Holstun (1953) pointed out that when cotton production is mechanized from all standpoints, excluding weed control, 30 to 40 man-hours per acre are required. Of these approximately 60 to 70 per cent are represented by hand labor for weed control. They state also that the more recent mechanical devices tested, such as hill-drop planters, mechanical and flame choppers, rotary weeders, and flame cultivators, are only partial answers to completely mechanized production.

The earliest work with herbicides promised advantages in increasing the efficiency of weed control procedures over conventional practices.

Porter *et al.* (1951) showed that three post-emergence applications of a special herbicidal oil followed by five flame cultivations controlled weeds in cotton satisfactorily with a reduction in man-hours per acre from 54 for standard cultivation and hoeing to 5½. The use of the pre-emergence herbicide DNBP followed by three oilings and five flamings reduced man-hours from 54 to 4, and added a possible insurance factor against early unfavorable weather for subsequent post-emergence weed control operations. The gross incomes per acre minus the weed control costs were $312.49, $313.42, and $310.40 for standard practices, three

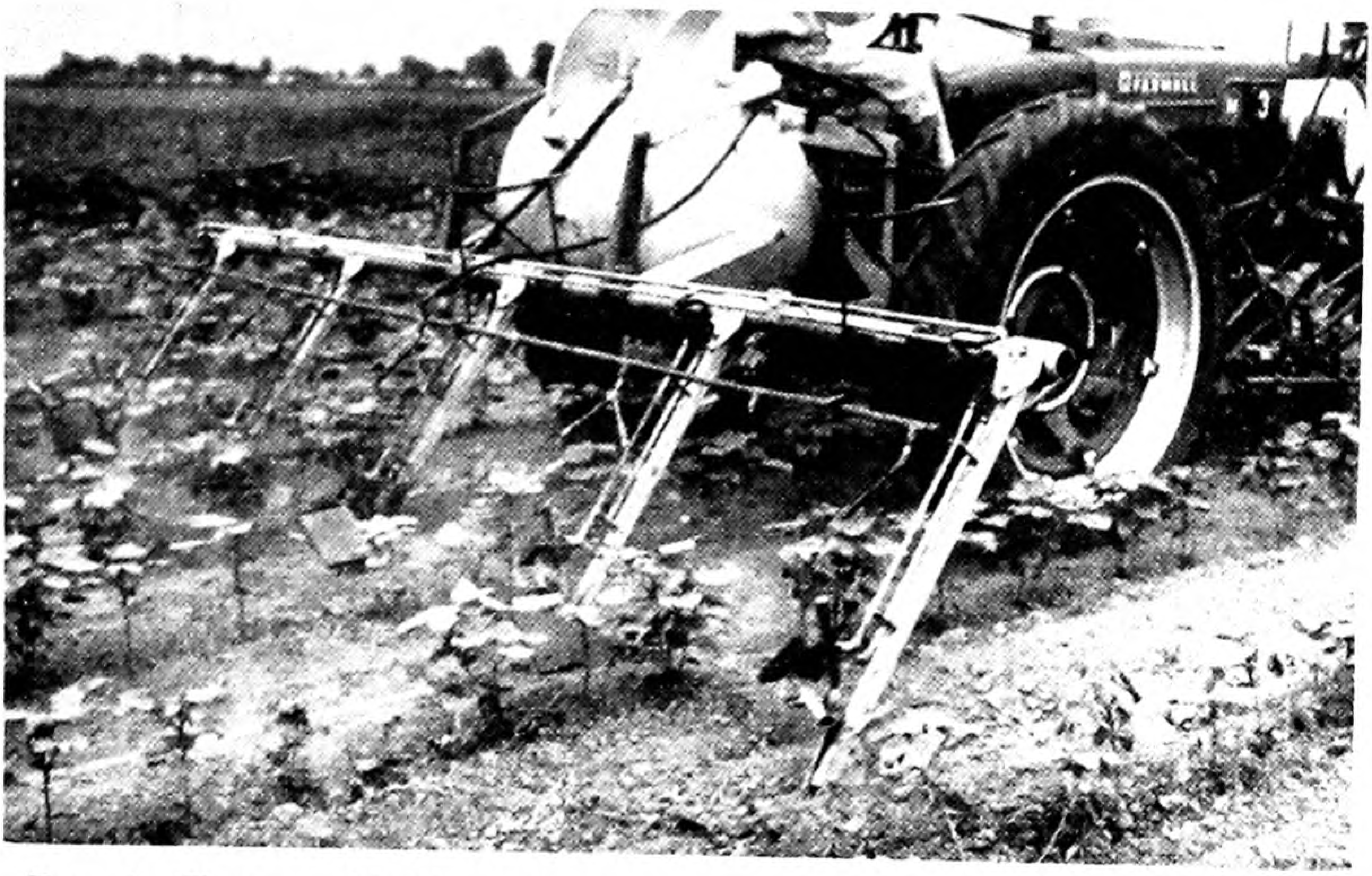

FIG. 4. Flame cultivation of cotton with tractor-mounted flat-type burners. Burners are operated at pressures of 45 to 55 p.s.i. and are set at an angle of approximately 45° with the ground and 8 to 10 inches away from row of cotton. (Courtesy Delta Branch Mississippi Experiment Station.)

oilings and five flamings, and pre-emergence plus three oilings and five flamings, respectively (Porter *et al.*, 1951). Additional studies have confirmed the usefulness of herbicides in reducing labor requirements (Table I).

Williams and Hinkle (1953a) have also obtained striking reductions in labor requirements by the use of DNBP, CIPC, and CMU as pre-emergence treatments and without significant influence upon yield. Their most effective treatments reduced hoeing time per acre from 29.6 hours for the conventional cultivation and hoeing practice to 5.3, 3.0, and 4.5 hours for DNBP, CIPC, and CMU, respectively.

From a four-year study in Mississippi, Harris (1954) reported that by using a combination of DNBP as a pre-emergence herbicide followed

TABLE I

Labor Costs for Various Weed Control Practices at St. Joseph, Louisiana. Cotton Planted and Treated with Pre-Emergence Materials on April 17, 1952. Post-Emergence Treatments Made May 15, 1952[1]

Treatments						
Pre-emergence		Post-emergence		Hoeing time/ acre, hours	Hoeing cost/ acre, dollars	Savings/ acre, excluding cost of herbicide
Herbicide	Lb./ acre[2]	Herbicide[3]	Rate/ acre[2]			
DNBP	6	—	—	31	15.50	$ 0.60
DNBP	6	Lion Oil 1	25 gal.	20	10.00	6.10
DNBP	6	DNBP	3 lb.	12	6.00	10.10
—	—	Lion Oil 1	25 gal.	27	13.50	2.60
—	—	DNBP	3 lb.	18	9.00	7.10
CIPC	6	—	—	4	2.00	14.10
CIPC	9	—	—	5	2.50	13.60
CIPC	12	—	—	3	1.50	14.60
—	—	Lion Oil 1	25 gal.	22	11.00	5.10
—	—	CIPC	6 lb.	26	13.00	3.10
CMU	1	—	—	7	3.50	12.60
CMU	1½	—	—	4	2.00	14.10
CMU	2	—	—	5	2.50	13.60
—	—	Lion Oil 1	25 gal.	25	12.50	3.60
—	—	CMU	1 lb.	16	8.00	8.10
None (Control)		None (Control)		32.2	16.10	—

[1] Stamper *et al.*, 1953.

[2] Broadcast rates. Divide by three for amount actually used per acre on band, except for Lion Oil 1 rates, which should be divided by five.

[3] DNBP = dinitro-*O*-sec. butyl phenol. CIPC = isopropyl-*N*-3-chlorophenyl carbamate. CMU = 3-(*p*-chlorophenyl)-1, 1-dimethyl urea.

by two post-emergence oil treatments, the average cost of weed control per pound of seed cotton was $0.0037 as compared to $0.0078 for hoeing. According to this worker, however, none of the cotton treated with the herbicides, without any hoeing, produced as much seed cotton as that in which weeds were controlled in the drill by hand hoeing alone.

An economic study of weed control practices on cotton plantations in the Yazoo-Mississippi Delta in 1952 showed that the added costs of pre- and post-emergence treatments combined with flame cultivation almost completely offset the reductions in cost made through lowering hand labor requirements (Table II). Notwithstanding, the use of herbi-

TABLE II

Costs in Dollars per Acre of Labor, Power, Machinery, and Materials for Different Combinations of Weed Control Practices, as Reported on 30 Farms, Yazoo-Mississippi Delta, 1952[1,2]

Weed control practices	Skilled labor	Common labor	Power & equipment	Materials[3]	Planting seed	Total
Drill plant and hand hoe	1.20	21.52	3.23	—	4.00	29.95
Hill-drop plant and hand hoe	1.17	20.82	3.17	—	1.60	26.76
Drill plant, cross plow, and hand hoe	1.19	7.14	3.20	—	4.00	15.53
Hill-drop plant, pre-emerge, and hand hoe	1.22	10.36	3.55	3.82	1.60	20.55
Hill-drop plant, oil, and hand hoe	1.16	8.92	3.49	3.33	1.60	18.50
Hill-drop plant, pre-emerge, oil, and hand hoe	1.18	6.51	3.86	6.32	1.60	19.47
Hill-drop plant, pre-emerge, oil, flame, and hand hoe	1.72	7.21	6.69	7.07	1.60	24.29

[1] Crowe and Holstun, 1953.

[2] Cost rates: Skilled labor $.50 per hour; common labor $.35 per hour; power and machinery costs per hour of operation: tractor $.90, planter $.90, cultivator $.40, spray machine—pre-emergence $.72, oil $.54, flame cultivation $1.86 per hour; pre-emergence materials $3.82 per acre; post-emergence oils $.25 per gallon.

[3] Includes pre-emergence chemicals and herbicidal oils.

cides in combination with other practices was shown to promote considerable savings in labor requirements and reduce weed control costs approximately $4.50 to $11.50 per acre (Table II). Cross-plowing was the cheapest method of controlling weeds in 1952 on the plantations studied, but it was pointed out that the technique presents a serious problem in mechanical harvesting as well as having other disadvantages (see Section II, 2*b*).

4. *Chemical Weed Control without Cultivation*

For a long time some workers have considered that cultivation of certain crops is of value only from the standpoint of controlling weeds. Other workers consider that in addition to control of weeds, cultivation promotes soil aeration and conservation of moisture. With the advent of selective herbicides the probabilities of producing certain row crops without cultivation increased many fold.

Leonard *et al.* (1947) reported that following a broadcast pre-emergence treatment of a DNBP, cotton grew to maturity practically free of weeds without any hoeing or cultivation. Harris (1951a) reported an extension of this work in which an excellent yield of cotton was produced without cultivation or hoeing by using a combination of DNBP and special post-emergence oils to control the weeds. Ennis and

Harris (1953) presented additional information on weed control in cotton grown with and without cultivation. They measured the yield response of the crop to cultivation, irrigation, and plant populations in which pre-emergence herbicides were applied broadcast to well-prepared soil (Table III). In view of the high cost of the herbicides

TABLE III

Influence of Pre- and Post-Emergence Herbicides and Plant Population upon the Yield of Seed Cotton and the Approximate Costs of Seed and Herbicides. No Cultivation or Hand Hoeing Was Done Except on the Control Plots. State College, Mississippi

Mean no. plants per acre	Row spacing, inches	Cost of herbicides	Cost of seed	Cost of hoeing & cult.	Total cost	Lb./acre seed cotton[1]
		1952 (10 lb./acre DNBP + 2 oilings)				
57,356	20	$32.75	$5.60	0	$38.25	2355
26,836	30	32.75	4.20	0	36.95	2164
22,015	40	32.75	2.80	0	35.55	2227
22,852	40	Control	2.80	$32.64	35.44	2218
		1953 (12 lb./acre CIPC + 8 lb./acre CIPC)				
105,197	20	$33.00	$5.60	0	$38.60	2396
70,132	30	33.00	4.20	0	37.20	2388
52,598	40	33.00	2.80	0	35.80	2205
52,598	40	Control	2.80	$31.08	33.88	2436

[1] Differences not significant.

applied and the additional cost of seed required for the higher plant populations, there was no particular advantage in producing cotton in close-spaced rows rather than in conventional-width rows. Cultivation did not promote an increase in yield of cotton, and the weeds were controlled satisfactorily without any hoeing or cultivation through use of the herbicides. Although cultivation was advantageous in aiding penetration of irrigation and rain water, the increased moisture was not reflected in yield under the conditions of these experiments. Supplemental irrigation also failed to promote yield increases in these experiments conducted on a clay loam soil.

In the event more effective herbicides or less costly herbicides are made available the practice of producing cotton without cultivation and hoeing after planting may become economically sound on certain soils. With present herbicides the practice does not show promise on areas infested with perennial weeds, such as nut grass, Johnson grass, and deep-rooted vine species.

5. *Problems Requiring Further Work*

Although enough progress has been made in cotton weed control research that all states in the rain-grown cotton area have guides to offer farmers who desire to use herbicides, numerous problems of a fundamental nature remain unsolved which limit development of the soundest principles for their employment as selective herbicides. The specific effects of different soil factors, physical and chemical, and environmental influences are largely unknown. A better understanding of the individual physical, chemical, and biological factors of different soils that may influence downward movement, persistence, and herbicidal action of the major herbicides is needed. More precise information is required on the influence of light, temperature, and moisture on the volatility and chemical stability of promising herbicides, as well as the effects of these factors upon the efficiency of the herbicides applied by different methods to control weeds selectively. Basic data on various herbicide-plant relationships, such as absorption by different plant parts and the action and fate of herbicides within the plant, would be equally useful in advancing efficient and economical usage of promising herbicides.

In addition to the requirements for additional information on mechanisms of herbicidal action and soil and environmental influences, there are some troublesome perennial weeds, such as Johnson grass, vine species, and nut grass, which are not controlled selectively by present herbicides nor by the cultural procedures being used in cotton. Vigorous efforts to discover new herbicides or to devise suitable mechanical methods to solve these problems are needed urgently.

III. Corn

1. *Nature of Problem*

Annual grasses and certain broadleaf weeds are particularly troublesome in corn grown in the South between time of crop emergence and the time first cultivation can be made. Under some favorable weather conditions early-season weeds do not present serious problems and corn may be kept reasonably free of weeds by cultivations. More commonly, however, wet weather conditions prevent timely cultural operations (see Section II, 1) and chemical weed control procedures are needed. Probably the most important weed problems in producing corn in the South are those created by the rapid growth of weeds such as annual morning-glory and cocklebur which develop after the last cultivation. These weeds lower mechanical picker efficiency and the vines

also promote lodging. Johnson grass and Bermuda grass are serious weeds in some fields.

2. *Herbicidal Usage*

a. Early-Season Weeds. 2,4-Dichlorophenoxyacetic acid (2,4-D) has shown promise as a pre-emergence herbicide to control annual weeds in corn and has been used more than any other herbicide. An important factor in determining the safety with which 2,4-D can be used as a pre-emergence spray is the depth of planting. Klingman (1948) found that corn planted 1¼ inch deep was not injured by 2,4-D but that planted ¾ inch deep or less was severely inhibited. The lack of rainfall within a few days following application of 2,4-D usually results in poor weed control (Freeman and Josephson, 1949). Under favorable conditions pre-emergence treatments with 2,4-D at rates of 1 to 1½ pound per acre can effectively replace two cultivations, provided a high percentage of the weeds present are responsive to the herbicide (Shear *et al.*, 1950).

The use of 2,4-D as a pre-emergence treatment on sandy soils is considered hazardous because rain may leach the herbicide downward to the crop seed and injure them. Clayey soils and those high in organic matter can usually be treated with 2,4-D at dosages up to 2.5 pounds per acre without significant damage to the crop. Best weed control has been obtained with least risk of crop injury when the herbicide is applied just prior to emergence of the crop (McMurray *et al.*, 1952; Shear *et al.*, 1950). The delayed treatment frequently cannot be made, however, because of rainfall. In addition, the delay in treatment necessitates an additional operation not required when planting and treatment are done simultaneously.

In areas where cotton and corn are grown in adjacent fields the drift hazard of 2,4-D to cotton has limited its use. Accordingly, a suitable substitute herbicide for 2,4-D not having serious drift hazards to cotton has been sought. Materials including DNBP, sodium 2,4-dichlorophenoxyethyl sulfate (SES), and others have been studied as pre-emergence herbicides for corn. No completely satisfactory substitute has been discovered. High cost in comparison to 2,4-D has deterred use of DNBP and SES. More recently some interest has been shown in the pre-emergence use of certain of the substituted urea herbicides at low dosages. Klingman and Davis (1954) reported more effective control of weeds with a 1 pound per acre application of 3-(3,4-dichlorophenyl)-1,1-dimethyl urea than was obtained with 2,4-D and the corn displayed no injury symptoms. The ureas present the same problems in corn as regards soil and climatic factors and persistence in soil as described earlier (see Section II, 3*b* (*4*)).

b. Late-Season Weeds. Broadleaf weeds such as ragweed, cocklebur, and annual morning-glory commonly infest many cornfields in mid-season to late season. Outstanding control of these weeds has been obtained by post-emergence application of 2,4-D at dosages of ⅓ to ½ pound per acre. A spray of the 2,4-D is applied in such a way as to avoid contact with the corn foliage except for a few inches at the soil level but to get good coverage of the weeds. Generally corn is most tolerant of 2,4-D when between 6 to 36 inches tall (Westmoreland and Klingman, 1954).

3. *New Herbicides and Techniques*

More recently some success has been obtained by Klingman and Davis (1954) in controlling weeds in corn by applying a water solution of ammonium nitrate containing a surface-active agent and 2,4-D, as a spray directed to the base of the corn plant and to weeds in the middle (Fig. 5). To achieve best results such sprays must be made when the

FIG. 5. Weed control in corn (left) obtained by use of a 2,4-D pre-emergence treatment followed by one cultivation and a post-emergence spray (when 20 inches tall) of ammonium nitrate solution (2.25 pounds N per gallon) containing 2,4-D propylene glycol butyl ether ester (⅛ pound acid equivalent per gallon). Volume of spray was *ca.* 18 gallons per acre. Row on right received three cultivations. (Courtesy North Carolina Agricultural Experiment Station.)

weeds are small and the crop is large enough to withstand the contact injury to the lower leaves. In addition to further studies of the efficiency of aqueous ammonium nitrate 2,4-D sprays as herbicides for corn, work is also needed to determine the comparative growth and yield responses of corn to the nitrogen derived from the aqueous ammonium nitrate sprays and to nitrogen from the sources usually recommended.

The use of contact herbicides such as DNBP as directional sprays for corn has shown promise for controlling small annual weeds and grass, but more work is required before recommendations can be made. Flame cultivation has shown good promise when used on corn of sufficient size to withstand the hot flame, but it has not proved satisfactory in controlling well-established grasses and broadleaves.

4. *Work Needed*

Large-scale application of 2,4-D to corn has not been practiced in most of the South. This may be attributed to the following: (1) a general farmer reluctance to employ the material because of unfavorable publicity arising from widespread damage to cotton following its introduction and careless application in rice and other crops; (2) inconsistent performance as a pre-emergence material for controlling weeds under varying soil and climatic conditions; (3) frequent low yields and unpredictable gross income per acre from corn as compared to cotton and other crops; (4) the practice in some areas of interplanting corn and soybeans, which are susceptible to 2,4-D; (5) lack of adequate research information and education in the proper use of the material in diversified farming areas; and (6) lack of suitable high clearance equipment on farms for applying 2,4-D sprays after last cultivation. A strong educational program is needed to encourage the use of 2,4-D on corn where its usage would be safe and efficiency of production increased.

The development of suitable methods for employing herbicides or cultural procedures to control Johnson grass infestations in corn lands is needed. In addition economical and efficient systemic herbicides similar to 2,4-D but not having a serious drift hazard to cotton are needed for the use on corn in areas where the two crops are grown adjacently.

IV. Soybeans

1. *Nature of Problem*

With good management weeds in soybeans do not present as serious a problem as in cotton. In Mississippi a delay in planting until after May 1 has shown distinct advantages in growing a crop relatively free

of weeds (Hartwig, 1954). Later planted soybeans emerge within a few days and develop rapidly enough to shade the soil and young weeds in a shorter time than soybeans planted under earlier cool weather conditions (Hartwig, 1954). Extended periods of wet weather, however, sometimes occur and heavy infestations of crab grass, pigweed, morning-glory, and other annual weeds develop in rows of the crop and the need for herbicides becomes almost as acute as in cotton (see Section II, 1).

The occurrence of morning-glory, pigweed, ragweed, cocklebur, and other species in soybeans not only causes yield reductions but lowers markedly the efficiency of combine harvesters. Suitable herbicides or techniques for preventing establishment of these weeds are needed on many farms of the South.

2. *Herbicidal Usage*

Considerable field-plot experimentation has been done on both pre-emergence and post-emergence herbicides for soybeans. The pre-emergence herbicides DNBP, CIPC, and sodium pentachlorophenate have shown most promise (Chappell, 1952, 1953, 1954; Williams and Hinkle, 1953b). In general, the pre-planting practices found most satisfactory for cotton have been shown advantageous in applying pre-emergence herbicides to soybeans (see Section II, 3*a*). However, the relatively high cost of pre-emergence herbicides and the lack of consistent yield increases from their use have prevented the formulation of general recommendations for pre-emergence spraying of soybeans to control weeds.

In 1949 Leonard and Harris (1950) found that soybeans were sufficiently tolerant of certain naphtha oils that selective control of young weeds in soybeans was feasible if directional sprays were employed (see Section II, 3*c* (*1*)). A single laterally directed application of the nonfortified oils found satisfactory for weeding cotton has been suggested for use on soybeans at a rate of 5 gallons per acre, 12 to 16 days after emergence of the crop (Edwards *et al.*, 1953). Cost per acre of the oil is about $1.00 to $1.25. Good control of annual weeds such as crab grass, pigweed, and morning-glory is usually obtained on top of the rows from one properly applied oil treatment.

3. *Work Needed*

Selective and economical herbicides for controlling large-growing annual weeds and certain perennials such as Johnson grass and *Brunnichia cirrhosa* (lady's-eardrop) in soybeans are needed for many areas. More satisfactory and economical pre-emergence herbicides are re-

quired for control of early-season weeds under weather conditions unsuitable for mechanical cultivation. Plant and soil relationships to herbicidal usage and environmental effects on herbicidal efficiency need elucidating for all herbicides under study for use on soybeans (see Section II, *3b* (*2*), (*3*)).

V. Sugar Cane

1. Nature of Problem

Virtually all of the approximately 350,000 acres of sugar cane grown in the United States for the manufacture of sugar are in Louisiana and Florida. About 85 per cent of the total acreage is produced in Louisiana. The nature of the weed problem in sugar cane in Louisiana has been presented admirably by Stamper and Chilton (1951a). They pointed out that Johnson grass infestations had become so severe on about 100,000 acres that a satisfactory control program was deemed necessary to obtain economic yields of sugar cane. Since sugar cane is allowed to produce three crops from a single planting before the entire land area is plowed for another planting, a perennial weed such as Johnson grass has excellent opportunities to increase and spread. Gibbens (1950) stated that the heavy infestations on some plantations had become so severe that it was possible to produce only a plant cane crop (1st year) and a first stubble crop (2nd year) rather than the ideal three crops, which includes a 2nd stubble crop (3rd year). Stamper and Chilton (1951b) estimated that as much as 100 miles of healthy Johnson grass rhizomes, weighing 9 tons or more, are present in a badly infested acre of sugar cane. Moreover, millions of ungerminated seed of the perennial are to be found in every acre of highly infested fields.

Commonly, land to be placed in sugar cane is fallow-plowed eight to ten times during the four to six months preceding planting. This practice kills efficiently the large Johnson grass plants including the rhizomes at a cost of about $15 per acre (Stamper and Chilton, 1951b). Notwithstanding, these workers stressed that literally thousands of viable seed remain in the soil after fallowing and threaten continuously to reinfest the new crop unless controlled. The rotation program to include the fallowing practice necessitates the use of about 100,000 acres in addition to the 300,000 acres actually producing sugar cane in that state. Inasmuch as cultural weed control procedures in combination with considerable hand labor have been inadequate to keep weeds from limiting the production and yields of sugar cane, considerable effort

has been given to a study of the usefulness of herbicides to promote better and more efficient weed control in this crop.

In Puerto Rico the use of 2,4-D alone over a period of years has resulted in a dominance of grassy weeds, especially perennials (Loustalot *et al.*, 1954). Therefore, weed control procedures are required that will eliminate both grass and broadleaf weeds. Work in Louisiana has been directed toward (1) the elimination of large Johnson grass plants and their rhizomes prior to planting a new crop, (2) control of Johnson grass seedlings during growth of crop, and (3) reduction of weed seed population in the soil by preventing the production of any new seed. In some fields broadleaf weeds are troublesome but they have not presented as serious control problems as Johnson grass because of their susceptibility to 2,4-D.

2. *Broadleaf Weeds*

Arceneaux and Hebert (1949) reported that the application of 2,4-D at a rate of 1 pound per acre was more effective and efficient in controlling alligator weed (*Alternantheria philoxeroides*), red morning-glory (*Ipomoea coccinea* L.), and cypress vine (*I. quamoclit* L.) in sugar cane than hoeing or flame cultivation. Further work in Louisiana and elsewhere has shown that broadleaf weeds are controlled by standard cultural practices and use of 2,4-D amine salts as follows: (1) a fall or late-summer pre-emergence treatment to freshly planted cane followed by (2) another treatment after fertilization in the spring and (3) a broadcast treatment after the last cultivation. Commonly, all treatments are made to bands 24 to 36 inches wide on top of the row except at the last treatment a broadcast application is made (Stamper and Chilton, 1953). Dosages of 2 pounds on a broadcast basis have been found most satisfactory. Broadleaf weeds in the two stubble crops are usually controlled satisfactorily by a broadcast application of 2,4-D after the last cultivation.

3. *Control of Johnson Grass*

a. Plant Cane. Preparatory to planting sugar cane in late August or September Stamper and Chilton (1953) found no satisfactory substitute for six to eight fallow plowings during the spring and summer to kill established Johnson grass. Following proper fallowing further weed control procedures are directed toward preventing re-establishment of the weed from seed. These workers have developed the following control methods for sugar cane.

The soil is made firm by rolling or cultipacking after planting in

August to October and then bands 36 inches wide on top of the row are treated with 2,4-D at a broadcast rate of 2 pounds acid equivalent per acre. After a rain, or about three weeks later, a drill treatment 24 inches wide is made with 90 per cent sodium trichloroacetate (TCA) on a broadcast basis of 15 to 21 pounds per acre. Middles and sides of the rows are cultivated as needed, and plants escaping the treatments are removed by hand labor.

In the spring, sides of the row are shaved or plowed (off-barred) into the middles and a band on the drill 24 to 30 inches wide is treated with 90% TCA at a calculated broadcast rate of 12 pounds per acre. This treatment is repeated within about one month but includes in addition 2 pounds acid equivalent of 2,4-D amine salts. Some roguing is practiced, and immediately after the last cultivation (layby) a blanket spray of the 2,4-D is made at an acid equivalent rate of 2 pounds per acre.

b. Stubble Cane. Shaving and off-barring is practiced as a first operation in the spring and a rotary hoe cultivation is desirable. Immediately following these operations and before emergence of Johnson grass shoots TCA is applied to 24- to 30-inch bands on top of the row at a calculated broadcast rate of 33 pounds per acre of a 90 per cent active material. A blanket treatment with 2,4-D is made at layby as described for plant cane. Johnson grass escaping the treatment is cut by hand with cane knives to prevent seed production. If Johnson grass infestation is spotty (one clump about every 50 row feet) and seedlings are few, individual spray treatments of all the top growth in the clumps are made at time of flowering with either sodium chlorate (1 to 1½ pounds per gallon of water plus ½ to ¾ pound of calcium chloride) or 90 per cent TCA (¾ pound per gallon of water).

4. *Economics of Chemical Weed Control*

Soon after the use of 2,4-D alone in sugar cane Best and Gibbens (1951) reported savings of about $8 per acre of cane. More recently, combination treatments of 2,4-D and TCA have shown consistent economic advantages in that yield increases and reduced labor requirements have more than offset the costs of the herbicides and their application (Hardcastle and Stamper, 1953).

5. *New Herbicides*

The progress made in developing efficient and economical uses for certain herbicides to control weeds in sugar cane is outstanding. More recent studies made with CMU and CIPC as pre-emergence herbicides for sugar cane (Loustalot *et al.*, 1954; Stamper and Hardcastle, 1954)

have shown good promise of controlling Johnson grass seedlings and certain annual weeds in sugar cane. Since the use of 2,4-D in some parts of the sugar cane area presents a drift hazard to cotton, materials which are efficient to control broadleaf weeds and which possess a low drift hazard are needed.

The new herbicide 2,2-dichloropropionic acid has shown good promise of controlling Johnson grass more efficiently as a foliage spray than TCA, and its usefulness in controlling this weed selectively in sugar cane is being explored in current work.

VI. Peanuts

1. Nature of Problem

Peanuts are grown extensively as a cash crop in southeastern Virginia and in the South Atlantic and Gulf states. The annual weeds commonly infesting cotton fields also present problems in peanuts (see Section II, 1). Under most conditions about one-third or more of the total preharvest man-hours are devoted to hand hoeing of weeds in this crop (Searcy, 1953a). The scarcity and higher costs of labor for hoeing have increased production costs excessively in many areas. Effective and efficient herbicides would reduce labor requirements and their attendant high costs. Moreover, better stands can be expected, because the losses resulting frequently from hoeing and covering of young plants during early cultivations are eliminated (Westmoreland and Klingman, 1953a).

2. Herbicides for Peanuts

The peanut plant in many respects is better suited to herbicidal usage than cotton. The seed is relatively large and may be planted 1 to 3 inches deep, depending on the soil type. This provides an increased safety feature in the use of pre-emergence herbicides that tend to leach downward following rainfall. In addition the young seedlings of peanuts are sturdy and have thick hypocotyls which make them more tolerant of the contact action of certain chemicals, e.g., DNBP, in the surface layer of soil than crop seedlings with relatively thin hypocotyls, such as cotton.

Beginning in 1948 studies were initiated at the Alabama Experiment Station to evaluate the potential usefulness of a selected group of chemicals for controlling weeds in peanuts (Scholl and Searcy, 1949). No treatment was as effective as hoeing but sodium pentachlorophenate, 2,4-D, and certain dinitro compounds showed enough promise to warrant further study.

Work by Shaw, York, and Gregory (1951) demonstrated that pre-emergence treatments with an alkanolamine salt of DNBP at a rate of 9 pounds per acre gave excellent weed control without causing adverse effects on crop stand, yield, or quality. Additional studies have indicated that the DNBP is safe to use as a pre-emergence treatment on peanuts but good weed control is not obtained consistently (see Section II, 3*b* (*2*)). Sodium pentachlorophenate has also produced good results as a pre-emergence herbicide but has performed more erratically than DNBP.

Pre-emergence use of 2,4-D has proved generally unsafe because rains occurring between time of treatment and emergence of peanuts may reduce severely growth and stands. Applications of 2,4-D delayed to coincide with the time peanut seedlings break the soil surface are more satisfactory than pre-emergence treatments (Westmoreland and Klingman, 1953b). Wet field conditions, however, commonly prevent the proper timing of such treatments. Moreover, the lack of adequate tolerance of peanuts to pre-emergence and post-emergence treatments with 2,4-D suggests that this herbicide has doubtful potentialities for use on this crop.

DNBP applied as a delayed pre-emergence treatment and even as a treatment to plants at the first foliage leaf stage has controlled weeds selectively in peanuts at lower costs than treatments immediately after planting (Westmoreland and Klingman, 1953b; Helms and Rodgers, 1953). Such treatments need more careful study under a wide range of climatic conditions to determine herbicidal efficiency and safety to the crop.

Sodium, 2,4-dichlorophenoxyethyl sulfate (SES) has given good results as a pre-emergence herbicide for peanuts in Georgia. The safety and efficiency with which this material can be used under varying rainfall conditions needs more study. The substituted urea herbicides, e.g., CMU, appear too injurious to peanuts for employment as selective herbicides.

Ideally, a pre-emergence herbicide for peanuts and other crops should resist downward movement in different soils by rainfall to a higher degree than is typical of most commercially available materials. Localization of an efficient herbicide in the top ½ inch of soil would promote control of annual weeds and lower chances of damage to the germinating crop. In addition, it is desirable that the crop possess some tolerance to the herbicide when exposed directly to it during germination and emergence. Present herbicides do not adequately meet these requirements. Certain of the new experimental carbamates need careful evaluation as pre-emergence herbicides for peanuts, and further

attempts to improve the herbicidal effectiveness and safety of current materials are needed. The use of contact-type and residual herbicides for post-emergence weed control in peanuts also is a promising area for further research.

VII. Tobacco

1. *Nature of Problem*

The production of tobacco requires more man-hours per acre than any other field crop. Much hand labor is involved in transplanting, hoeing, removing axillary shoots ("suckers"), and harvesting. Because most farmers grow only a limited acreage of this crop, there is usually sufficient labor available for hoeing the weeds not controlled by cultivation. Notwithstanding, the labor required for hand hoeing of tobacco could be employed for other productive purposes by tobacco farmers with other enterprises if safe, economical, and efficient herbicides were available to control weeds.

The most critical weed problem in producing tobacco occurs in the beds used for growing plants to an appropriate size for transplanting to the field. In the absence of suitable herbicides to control weeds in tobacco plant beds, they must be pulled out by hand. This operation is meticulous and time-consuming.

2. *Plant Bed Weed Control*

Hill *et al.* (1953) published the results of a large amount of work done in evaluating chemicals for use in controlling weeds in tobacco plant beds. The most effective herbicides studied was methyl bromide. The findings of Hill *et al.* (1953) corroborated earlier findings of Freeman (1949) that methyl bromide has good potentialities for killing weed seeds in plant bed soils. This material is being used currently on a fairly extensive basis in tobacco plant beds. It is applied under a gas-proof cover at a rate of 1 pound per 100 square feet. Treatment exposure ranges from 24 to 48 hours at outside temperatures of 60° to 50° F., respectively (Bennett *et al.*, 1953). Beds can be planted safely within 2 to 3 days after removing the cover. Methyl bromide controls virtually all troublesome weeds in tobacco plant beds and is fulfilling a long-standing need of tobacco producers.

3. *Herbicide Usage in Tobacco Fields*

Since 1949 workers at the North Carolina Experiment Station have studied various herbicides applied at different intervals before transplanting, at transplanting, and after transplanting in an effort to de-

velop safe methods of using herbicides to control weeds in field-grown tobacco (Wilson and Klingman, 1952; Coggins *et al.*, 1954). Insufficient progress has been made to formulate any recommendations. Post-transplanting treatments with 2,4-dichlorophenoxyethyl benzoate, dichloral urea, sodium 2,4,5-trichlorophenoxyethyl sulfate, and other similar materials have shown sufficient promise that continued experimentation is warranted.

VIII. Rice

1. Nature of Problem

The conditions under which rice is grown are favorable for the growth of aquatic and semiaquatic weeds. Some rice fields have become so infested with certain broadleaf weeds that rice production is not profitable unless the weeds are controlled. The most common and troublesome weeds in rice fields of the South are coffeeweed (*Sesbania macrocarpa* Muhl.), Mexican weed (*Caperonia palustris*), curly indigo (*Aeschynomene virginica* L.), red rice (*Oryza sativa* L.), *Echinochloa* spp., *Brachiaria* spp., and *Cyperus* spp. The grasses are particularly serious when rains occur soon after planting or during dry periods when it becomes necessary to flood the fields to promote germination of the rice (Ryker, 1950). Under these conditions the grasses emerge concurrently with the rice and the common practice of early flooding of rice does not give satisfactory control of the weeds.

Grassy weeds are heavy competitors for water and nutrients, and they are becoming an increasingly serious problem in old rice-growing areas. No simple and completely reliable control procedures are available for controlling them. Red rice presents milling difficulties and lowers the market value of the crop. It belongs to the same species as white rice and is introduced and spread in rice fields by using seed that contains red grains. Red rice seed shatter easily and remain viable in soil for several years, thus presenting complications to a control program when once introduced.

Some outstanding success has been attained in controlling broadleaf weeds with 2,4-D and similar materials, but an acute problem arises in many rice areas from 2,4-D drift damage to cotton and safer materials are needed urgently.

2. Weed Control Procedures

a. Broadleaf Weeds. A sound practice to promote rice fields free of weeds is summer or fall plowing followed by several diskings timed to kill weed seedlings before rice is planted (Reynolds, 1954). Cultural

weed control practices fail to give satisfactory results in many instances, however, because adverse weather or other circumstances prevent performance of necessary operations. Under such situations the use of an efficient and safe herbicide is of substantial value.

One of the first large-scale agricultural uses of 2,4-D in the South was for controlling certain broadleaf weeds in rice. The excellent control of the three principal broadleaf weeds in rice, i.e., coffeeweed, curly indigo, and Mexican weed, by 2,4-D (Ryker, 1949) stimulated immediate interest in use of the material. The critical need of an herbicide to control broadleaf weeds on many rice farms advanced the use of 2,4-D on a fairly broad basis before proper information was available on the effects of 2,4-D upon the rice plant itself. Fortunately, by coincidence rice was sufficiently tolerant of 2,4-D when the broadleaf weed problems were recognized as critical and treatments were made that few or no serious yield reductions occurred. Another example of premature adoption of a practice was the aerial application of dusts containing 2,4-D in some of the earliest work. Drift damage to cotton was so widespread that legislation was enacted prohibiting the application of 2,4-D dusts from airplanes.

Many of the unknown factors governing the safe and efficient use of 2,4-D on rice have been elucidated within the last few years. Best results can be expected from treatments made when rice is four to six weeks old and the weeds are succulent and growing rapidly. Dosages of ½ to 1 pound acid equivalent per acre give good control of the common broadleaf weeds without yield reductions. The lower rates are used when applications are made to the youngest rice (three to four weeks). Treatments made to seedling rice (one to two weeks old) and at the boot to flowering stage may depress yields significantly (Jones *et al.*, 1952).

The problem of drift hazard to cotton from 2,4-D applications to rice has stimulated a search for safer materials. 2-Methyl, 4-chlorophenoxyacetic acid (MCP) and 2,4,5-trichlorophenoxyacetic acid, (2,4,5-T) treatments to broadleaf weeds in rice have given good control without significant injury to rice (Davis, 1954). Unpublished work in Mississippi shows that spray drift of these latter materials is less injurious to cotton that 2,4-D, but the safety margin is not great enough to satisfy needs. More recently further emphasis has been placed on developing herbicides or methods of applications to minimize drift problems.

b. Grassy Weeds. When feasible, water planting of rice promotes development of the crop before most grassy weeds can become established. This practice is not followed widely because of the additional

cost of flooding, airplane seeding, and other factors. Young grass seedlings may also be controlled by the judicious covering of the weeds with water without injury to seedling rice, but grasses that emerge at the same time as rice are not controlled satisfactorily. Experiments to employ herbicides for selective control of grassy weeds in rice have not yielded promising results. Red rice may be hand-rogued from fields with light infestations, but this is not practical when plants are numerous; the best control is to avoid using seed containing red rice and thus prevent its entry to clean fields (Jones *et al.*, 1952).

Various cultural and management practices in combination with appropriate herbicidal treatments are worthy of intensive exploration to develop procedures for the control of the important grassy weeds in rice, including red rice.

IX. Pastures

1. *Nature of Problem*

Weeds limit to some extent productiveness of pastures and forage crops on virtually all farms, even though proved practices of fertilization, recommended species, and management are followed. Heavy populations of weed seeds occur in many pastures because weeds have been permitted to produce seeds year after year. Mowing weeds from pastures gives temporary control, but the terrain of many pastures does not permit the operation of mowing machines. Accordingly, weeds too frequently grow unabated. Many farmers have created weed problems by actually sowing weed seeds with farm seeds. More stringent weed laws and educational programs to eliminate the sale and usage of weed-contaminated legume and grass seeds are indicated.

Often weeds prevent the proper establishment of desirable species, and not infrequently they encroach upon areas following establishment of pastures and forage crops. Weeds compete for water, nutrients, and light and inevitably inflict serious losses not only in stands of desirable species but also in quality and yields of forage. Wild onion and garlic (*Allium* spp.), and bitterweed (*Helenium tenuifolium* Nutt.) are commonly present in many pastures of the South, and these impart undesirable flavors to milk which result in lower quality and economic returns to dairymen. Annually some livestock die from consuming poisonous weeds present to some extent in grazing lands of the humid portion of the southern region and rather commonly in range lands of Texas and Oklahoma. Control of these species is an important problem in producing livestock.

Accurate estimates of damage done by weeds are sometimes difficult

because weeds ofttimes become serious only after stands of desirable species have been reduced by overgrazing, poor fertility levels, cold injury, drought, insects, diseases, or other causes. Irrespective of the factor or factors which promote weed problems in pastures and forage crops the occurrence of weeds is costly and economical methods for their control or eradication are needed promptly.

2. *Establishment Problems*

One of the best weed control procedures to follow in establishing small-seeded grasses and legumes for forage is to fallow-cultivate the land during the summer prior to seeding with a view to reducing the population of weed seeds that may germinate and grow concurrently with the forage species. With adequate fertilization and soil moisture desirable species seeded in the fall may make enough growth during the cool months to provide sufficient competition to suppress annual weeds that germinate in the spring. Notwithstanding, annual winter weeds such as henbit (*Lamium* spp.), common chickweed (*Stellaria media* (L.) Cyrillo), little barley (*Hordeum pusillum* Nutt.), and others frequently infest fall-seeded areas, with a resultant depression of vigor and reduced stands of forage species. As a consequence, explorations have been made on a moderate basis to determine the usefulness of herbicides in promoting the establishment of weed-free forages and in particular, alfalfa (*Medicago sativa* L.).

A study was made by Johnson *et al.* (1949) to evaluate the effectiveness of selected herbicides for controlling winter weeds in newly seeded alfalfa. These workers found that isopropyl *N*-phenyl carbamate (IPC) applied in December in a dust formulation controlled little barley satisfactorily but broadleaf weeds flourished. Treatments made to alfalfa in the three-leaf stage with either dinitro *o*-secondary amyl phenol (DNAP) or DNBP at a rate of 2 pints per acre of formulated herbicide gave good control of henbit, common chickweed, and Shepherd's purse (*Capsella Bursa-pastoris* (L.) Medic.) but failed to control little barley. Shaw, Hauser, and Woodhouse (1951) presented results of work done on seedling alfalfa in which the triethanolamine salt of DNBP applied in January at a rate of 2 pounds per acre in 20 gallons water gave excellent control of winter annual weeds and promoted excellent stands and yields of alfalfa. An ammonium salt of DNBP was less effective than the triethanolamine salt used in their work.

On the basis of work done over a several-year period Shear (1954) emphasized that if winter annual weeds occur in areas seeded to alfalfa, control programs should be initiated the first winter in order to prevent the production of weed seeds. This was urged because the weed seeds

inevitably germinate after any herbicide has dissipated and thereby threaten infestation of the crop in succeeding winters. Shear found certain DNBP formulations effective in killing young chickweed but believes it is necessary to employ a combination of DNBP and fuel oil to kill older chickweed. The latter treatment is too expensive, according to Shear, and also fails to control German moss (*Scleranthus annus* L.), a serious pest in Virginia. Moreover, the usage of DNBP to control chickweed in established alfalfa requires late cutting of the alfalfa; the damage done by the late cutting more than offsets any benefits derived from weed control, according to Shear. In recent studies this worker has obtained good control of chickweed, German moss, and an annual brome grass by late fall or winter treatments with CIPC at dosages of 3 to 4 pounds per acre; such rates are reported as being used safely on well-established fall-seeded alfalfa during the first winter.

Pastures seeded to legumes and grasses present almost insurmountable problems as regards the usage of herbicides to control weeds during the germination and seedling stages of the pasture species. Some herbicides show differential action between grasses and legumes, but no herbicide has been discovered with sufficient specificity of action to use safely as pre-emergence treatments on newly planted mixtures of grasses and legumes.

Sheets *et al.* (1954) have studied the usefulness of several chemicals applied as preplanting, pre-emergence, and post-emergence sprays for controlling weeds in the establishment of alfalfa, Ladino clover (*Trifolium repens* L.), and orchard grass (*Dactylis glomerata* L.). These workers found post-emergence treatments were generally more promising than preplanting and pre-emergence applications. In pure stands of alfalfa and Ladino clovers IPC used pre-emergently at a rate of 4 pounds per acre showed promise for controlling some weeds, and both IPC and CIPC gave control of seedling grasses without crop injury when applied as post-emergence winter treatments. Neither IPC nor CIPC offered promise as pre-emergence herbicides where mixed stands of legumes and grasses were involved. An alkanolamine salt of DNBP applied at rates up to 2 pounds per acre in January under North Carolina conditions controlled many annual broadleaf weeds without significant injury to alfalfa, Ladino clover, and orchard grass.

Many of the experimental herbicides are exhibiting marked specificity of action, and weed research men need to evaluate carefully the potentialities of each promising one to determine possible chemical methods for controlling weeds in newly established pastures. Combinations of preplanting cultural and herbicidal treatments should be studied more exhaustively where different weed problems are encoun-

tered. The post-emergence usage of herbicides requires additional work to determine the effect on crops and weeds at different growth stages and under varying soil and environmental conditions.

Perennial woody plants are frequently removed mechanically from lands to be utilized for improved pasture. Vigorous resprouting from the roots of the woody species presents serious problems particularly when the soil is heavily fertilized. Chemical treatment of the brush after legumes and grasses are established is not satisfactory because of damage to the forage crops. Prior to clearing land of woody species, however, the usage of brush-killing chemicals appears to have a definite place. Little or no work has been done on this problem except where herbicides have been used on brush species of range lands with a view to promoting growth of native grasses (Elwell, 1954). With trends toward increased grassland farming in the South the employment of herbicides to prevent brush reinfestation of wooded areas newly converted to improved pastures should command the efforts of research men.

3. *Maintenance Problems*

a. Permanent Pastures. Permanent pastures and unimproved grazing lands are infested commonly with weeds that lower markedly the yields and quality of forage. Particularly troublesome are certain spring and summer annuals, namely, bitterweed, ragweed (*Ambrosia* spp.), *Plantago* spp., dog fennel (*Anthemis cotula* L.), *Croton* spp., crab grass (*Digitaria* spp.), poor Joe (*Diodia teres* Walt.), oxeye daisy (*Chrysanthemum leucanthemum* L.), and others. Among the perennials presenting problems are wild onion and garlic, horse nettle (*Solanum carolinense* L.), dock (*Rumex* spp.), ironweed (*Vernonia* spp.), yarrow (*Achillea millefolium* L.), certain woody species, and other broad-leafed weeds. When lands once become infested with these weeds, the problems of controlling them are unending. Mechanical removal by mowing keeps some of the weeds suppressed temporarily and also aids materially in reducing seed production. The need for economical selective herbicides to control the numerous pasture weeds is acute.

The herbicide 2,4-D has shown much promise for controlling ragweed, bitterweed, *Plantago* spp., sumpweed (*Iva ciliata* Willd.), and other broadleaf weeds in permanent pastures at low cost without damaging significantly the forage production. Harris (1953) found that treatments of ⅔ to 1 pound per acre of an amine form of 2,4-D in April and again in July was highly effective in controlling most broadleaf weeds in a Mississippi permanent pasture consisting principally of Bermuda grass (*Cynodon dactylon* (L.) Pers.), Dallis grass (*Paspalum*

dilatatum Poir.), Johnson grass, lespedeza (*Lespedeza striata* (Thunb.) H. & A.), and Ladino clover. This worker reported an increase in desirable species in plots treated with 2,4-D, whereas the weed competition in the mowed and untreated plots reduced the population of forage species. Drift hazard to cotton from 2,4-D, however, has been a deterrent to its use on a broad basis in some southern states. Other factors contributing to inadequate use of this valuable herbicide are the relatively high cost of spray machines, and poor educational programs to train farmers how to use spray equipment and make safe applications. Notwithstanding, many permanent pastures with white or Ladino clovers as the principal legumes are being sprayed with 2,4-D prior to emergence of cotton, and farmers are generally pleased with the results. New developments in spray equipment such as the cluster nozzles permit spraying of rough terrain and other areas where mowing or treatment with conventional boom sprayers is impractical. There is every reason to expect a marked increase in the usage of 2,4-D or similar low-cost herbicides for weed control in many pastures of the South in the future.

Wild onion and garlic have responded erratically to 2,4-D applications. Sell (1948) reported 80 to 87 per cent kills of wild garlic from a 2,4-D ester applied in late January or February at dosages of 2.5 to 3.3 pounds per acre in 100 gallons water. He emphasized that most bulblets had sprouted by February under Georgia conditions and treatments should be made to coincide with the time the maximum number of bulblets have sprouted. By March he found 30 per cent of the bulbs were forming new bulblets. In additional studies Sell *et al.* (1949) found that by treatment of wild garlic in February with a 2,4-D ester formulation for two consecutive years the original population was reduced as much as 98 per cent. Other workers (McMurray *et al.*, 1952) have pointed out that 2,4-D kills only the garlic plants that have shoots, and sufficient dormant bulblets remain in the soil to necessitate treatments over a two- or three-year period to achieve eradication. Because of the cost factor presented these latter workers suggested a combination of cultural practices and 2,4-D treatment for controlling this pasture weed.

Some woody perennials are increasing in many permanent grazing areas of the deep South. Among those that have caused considerable concern are Chickasaw rose (*Rosa bracteata* Wendl.) and palmetto (*Serrenao repens* and *Sabal minor*). Searcy (1953b) estimated that enough land is covered by *R. bracteata* in nine counties in Alabama to produce 1.5 million pounds of live beef annually, at the present rate of stocking, if the species was removed. He reports that mechanical methods of control at best are only a partial and temporary solution to the problem. Searcy found that seedling plants and sprouts from old

plants were killed satisfactorily by 2,4-D but that one application of 2,4-D amine salt as a wetting spray at concentrations up to 4 pounds per 100 gallons water failed to kill large clumps of Chickasaw rose. Oil was a poorer carrier for 2,4-D than water and 2,4,5-T was found to be less effective than 2,4-D. This worker states that treatments with 2,4-D appear to provide a means of keeping the pest under control but that eradication with 2,4-D sprays is attained only with difficulty.

Studies by Gertsch and Ryker (1951) and Prescott and Stamper (1954) on *R. bracteata* are in general agreement with those of Searcy given above. Prescott and Stamper found that winter treatments (December) under Louisiana conditions promoted a higher kill of *R. bracteata* than spring applications (April); effective dosages were wetting sprays of 4 pounds 2,4-D per 100 gallons water.

Nation (1951) recorded that saw palmetto (*S. repens*) in Florida responded slowly to saturation oil-emulsion sprays of 2,4,5-T propylene glycol butyl ether ester, but after several months good control was observed. Prescott and Stamper (1954) obtained excellent control of palmetto (*Sabal minor*) in Louisiana with 2,4-D or 2,4,5-T applied in March or in August. Kerosene and Varsol were employed as carriers and the herbicides were used at concentrations of 4 pounds per 100 gallons oil.

Persimmon (*Diospyros virginiana* L.) as well as other woody species poses problems in many permanent pastures. Results of attempts to control persimmon with herbicides have been inconsistent. More work is needed to discover satisfactory herbicidal treatments or other methods for controlling this pest and others in grazing lands.

Although 2,4-D controls satisfactorily many broadleaf weeds, some species are resistant, e.g., horse nettle and cypress weed (*Eupatorium capillifolium* Lam.). Other low-cost herbicides are needed for pasture weed control that can be applied without injury to forage species and that give control of species resistant to 2,4-D. Therefore, a search for materials to control specific troublesome weeds should be initiated. Mowing and herbicidal treatments in combination with practices that promote the development of dense sods need careful study with a view to improving the weed control achieved over that of any single practice.

Harris (1951b) gave results obtained from applications of a diethanolamine salt of 1,2-dihydropyridazine-3,6-dione (maleic hydrazide) to wild onion (*A. canadense* L.). He found that treatments of 3 pounds per acre in November gave 98 per cent control and a similar treatment in March gave 80 per cent control. The inclusion of a surface-active agent in the spray solution was deemed highly important to achieve satisfactory results with maleic hydrazide. Peek and Hinkle

(1952) have confirmed Harris' results. They found that treatments of 3 pounds per acre of maleic hydrazide in March and again in April gave excellent control of wild onion. Applications up to 18 pounds per acre showed no advantage over 3 pounds per acre. The high cost of maleic hydrazide is a deterrent to its use by farmers for weed control. In addition it is safe to use only on permanent pastures or other areas where desirable species are dormant at time of treatment.

Henbit, chickweed, and annual grasses are also problems in established grass-legume mixtures and the usage of herbicides to prevent the germination of these weeds offers sufficient promise to warrant intensive study on different types of pastures.

b. Winter Pastures. Dock, vetch (*Vicia* spp.), and *Allium* spp. are especially serious late-winter and early-spring weed pests in pastures seeded to small grain, ryegrass, and other species. Dock may be controlled satisfactorily by spray treatments with 2,4-D in the fall when dock begins growth or during early spring when rapid growth is being made. Treatments should be made when forage species involved are most tolerant to the 2,4-D. Vetch is responsive to 2,4-D and 2,4,5,-T and good control is usually achieved from treatments made in early spring. The 2,4,5-T has been found less inhibitory to dock than 2,4-D. Therefore, if both vetch and dock occur as weeds in pastures, early-spring treatments with 2,4-D are recommended (Edwards *et al.*, 1953).

Klingman (1952) described a method of controlling wild garlic in fall-seeded oats which involved adequate fertilization to provide vigorous competition for the garlic developing in the spring and which combined the application of 2,4-D triethanolamine salt, in March at rates of 1 to 1½ pounds per acre. This worker reported 100 per cent control of garlic by this procedure, but the oats were not utilized for grazing. The practicability of adapting the principle of combining competition with 2,4-D usage for control of *Allium* and other weeds in small grains and other species used for winter pastures appears worthy of exploration.

X. Future Prospects

An attempt has been made in this review to outline some of the progress made in utilizing chemicals for controlling weeds in crops of the southern United States. The number of important unsolved problems confronting weed research men is large and impressive. Weather factors, especially temperature and rainfall, and soil factors present challenging problems that demand careful study as they relate to each promising herbicide. Equally important are the requirements for studying the mechanisms of herbicidal actions, the life cycles of weeds,

the ecological and physiological problems created by herbicidal usage, etc. It is apparent that the need is acute for more properly trained persons to conduct productive research in the rapidly expanding field of chemical weed control. Moreover, the future rate of acceptance by farmers of the technological advances made possible by the use of herbicides is largely dependent upon the rapidity with which educational workers are trained and employed to aid farmers in adopting the advances.

In spite of the numerous problems that remain to be solved remarkable progress has been made in devising procedures for controlling weeds with herbicides in certain crops of the South, notably cotton and sugar cane. These developments have occurred following research by a few persons over the relatively short interval of five to ten years. There is every reason to expect increased public and private support of weed control research. This support can be anticipated because more efficient control of weeds should decrease crop production costs materially, with attendant lower costs to consumers at home and with more competitive prices abroad. New herbicides exhibiting more selective action than present ones are being synthesized in increasing numbers, and future prospects are bright for more efficient and economical herbicides to mitigate virtually all major weed problems. Expanded research coupled with strong educational programs may make possible, within a few years, the usage of herbicides on a basis comparable to that of fertilizers and insecticides.

The acceptance and large-scale employment of herbicides inevitably will present new problems to agronomists, agricultural engineers, and other agricultural workers. Changes in some of the present-day agronomic practices and modification in design of farm equipment may be required if herbicides are utilized routinely and extensively to control weeds. For example, conventional spacing of rows for many crops was adopted because they are suitable for the operation of mule-drawn implements used primarily to keep weeds under control. With the wide adoption of herbicides to control weeds, changes in the crop row spacings commonly used today are in prospect. Such changes may require drastic modifications in present-day farm equipment or the design of new equipment to produce the crops. To cite another example, many current recommendations for the placement of fertilizers in soil emphasize that the fertilizers should be placed deep enough so that the roots of weed seedlings cannot absorb the nutrients before the crop plants become established. The employment of satisfactory pre-emergence herbicides to control weeds presents new opportunities for more efficient placement of both liquid and solid fertilizers. Far-reaching

changes in other agronomic practices may become mandatory as modern weed control materials and methods are broadly utilized in crop production.

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Mineralization of Organic Nitrogen in Soil

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CONTENTS

I. Introduction

Though as far back as in the years between 1850 and 1890 it had already been shown that plants under certain conditions can utilize organic compounds for their nitrogen nutrition, the general opinion became gradually accepted that the normal nitrogen uptake was possible only with ammonia or nitrate compounds. This opinion prevails to the present day, though some modern investigations have demonstrated the possibility of the uptake of soluble organic substances by higher plants (Section III). A logical consequence hereof, however, was that soon after the triumph of the ideas of Liebig, and after the fundamental publications of Pasteur, Boussingault, Müntz, Hoppe-Seyler, Dehérain, Schlösing, Stoklasa, Beijerinck, and Winogradsky, all investigators realized the importance of the process of mineralization of organic substances in soil by microbes. Löhnis (1910) formulated it clearly by saying that, "Da die Intensität der in einem bestimmten Boden verlaufenden Ammoniakbildung offenbar massgebend ist für die Ausnutzung der auf dem betreffenden Felde angewandten stickstoffhaltigen Düngemittel organischen Ursprunges bzw. für die Verwertung der in den Ernterückständen festgelegten Nährstoffquantitäten, so muss demgemäss eine zweckentsprechende Prüfung der ammoniakbildenden Kraft der betreffenden Erde einen Anhalt geben für die zu erwartende Wirkung einer Düngung mit Stickstoffhaltigen organischen Substanzen," thus underlining the importance of this field of research. Therefore, although the mineralization of nitrogen must consequently be recognized as a very old problem—even the overestimation of the importance of humus for plant nutrition by Albrecht Thaer at the beginning of the 19th century was a result of the conviction of mineralization of organic compounds in soil—it still occupies a prominent position in studies about plant nutrition. The aim of this review is to summarize the important papers in this field of research, beginning with the years preceding World War II.

Partly because in most normal soils the oxidation of ammonia to nitrite and nitrate proceeds so fast that the formation of ammonia from the organic compounds may be obscured, and the only end product of the mineralization seems to be nitrate, the nitrification *sensu strictu* received disproportionately much attention, whereas the preceding ammonification often was neglected; this was especially so since around the years 1900 to 1920 the NO_3-N was estimated to be a better source of nitrogen than NH_4-N for uptake by plants. This situation is still not entirely overcome, and it will become apparent from the following review that many workers up to the present time for the sake of con-

venience designate not only the oxidation of NH_4 to NO_3 but the whole process of mineralization of organic nitrogen as "nitrification." The rather confusing application of this expression to the entire mineralization is, however, so general that it seemed impracticable to avoid it systematically in the subsequent discussions.

Another remark, necessary as a premise here, is that, if all aspects were dealt with in full, the subject of the mineralization of nitrogen would be too broad for review in this paper. Therefore it was decided to omit some rather specialized aspects of this whole complex problem, such as the denitrification of nitric compounds. Similarly the specialized papers dealing with the physiology, morphology, and taxonomy of the nitrifying organisms are also excluded. Consequently only the different aspects of the mineralization of organic nitrogen will be reviewed herein.

II. Liberation of Nitrogen from Native Humus and Organic Additives

The recognition of the liberation of ammonia as the first form of mineral nitrogen in any breakdown of nitrogen-containing organic substances was expressed by Marchal in 1893, and was subsequently the subject of innumerable papers. The process of oxidation of ammonia to nitrate via nitrite was elucidated by the studies of Schloesing and Müntz (1877–1878), Warington (1878–1891), Winogradsky (1890), Winogradsky and Omeliansky (1899a, b), and others. Consequently the fundamental interpretation of the whole process of mineralization and nitrification had already been given as far back as the last decades of the 19th century, and this interpretation still is accepted as correct. The general outline has since been criticized in some details, as will be mentioned in some of the subsequent paragraphs, but the validity of the classical interpretation of the process of microbial mineralization of nitrogen following the stages:

$$\underbrace{\text{Organic N} \rightarrow \text{Ammonia}}_{\text{Ammonification}} \rightarrow \underbrace{\text{Nitrite} \rightarrow \text{Nitrate}}_{\text{Nitrification}}$$

has more than once been proved, at least for the bulk of the mineralization of nitrogen in soil. But the different aspects of the application of the above general principle to plant nutrition, pedology, and agriculture are still being actively studied, and many problems in these applied fields of research are awaiting further elucidation.

The number of the earlier investigations of the amount of mineral nitrogen in soils and its fluctuations is very high. Most of them are dis-

cussed in some review papers (King and Whitson, 1901; Greaves *et al.*, 1917; Gowda, 1924; Blanck, 1931; Waksman, 1932; Russell, 1937; Richardson, 1938).

Two papers from that period must be mentioned here separately as being perhaps the best presentations of the problem as it was seen in those days: (1) Russell (1914) and (2) Crowther and Mirchandani (1931).

The majority of these earlier investigators determined the NO_3-N or the total mineral N(NO_3-N + NH_4-N + NO_2-N) only in the field, and deduced from these periodically collected data their conclusions about the changes in the mineral N content as influenced by season, crops, climate, moisture, temperature, structure of the soil, and its total nitrogen and humus content. But soon the incubation method in one form or another was introduced, whereby not only could the changes in the mineral N content of the soil in the natural conditions be followed, but also the "nitrifying capacity" or the amount of "mineralizable nitrogen" could be determined. A more detailed review of the different "incubation" methods or "nitrification" tests will be given in Section IV. A third method, also applied very early, was the study of the nitrogen balance in lysimeter studies. However the application of carefully constructed large lysimeters, being a very expensive procedure, was restricted to only a few investigations (Dehérain, 1902; Miller, 1906; Russell and Richards, 1920; Leather, 1911; Burt and Leather, 1909; Lyon and Bizzell, 1918; Lyon with collaborators, 1930, 1936; Mooers *et al.*, 1948; Bizzell, 1944), and during recent years practically no lysimeter studies have been applied to the problems of nitrogen mineralization. Intermediate between field trials and lysimeter studies are some of the pot experiments, in which an arrangement was provided for drainage and analyses of the water leaching out of the pots.

Though many cases of fundamentally divergent opinions can be found in the extensive older literature on nitrogen mineralization and nitrogen balances, some principal rules were practically accepted as proved in the years immediately preceding World War II.

1. In ordinary soils NO_2-N was never found to accumulate, and even the NH_4-stage of mineralization is of importance only under exceptional conditions. It was therefore understood that under normal conditions, the rate of oxidation of NO_2 to NO_3 is higher than that of the formation of NO_2 and that the latter again is equivalent to or higher than the rate of ammonification.

2. In fallow soil the mineral N content is lowest during the winter, rises rapidly in spring and the first part of the summer season, maintains itself on a rather high level throughout the summer, and then

drops rapidly to the low winter level with the onset of the rains in autumn.

3. In cropped land a second minimum is observed in midsummer, during maximal growth of the plants, followed by a second maximum after harvest. It is therefore evident that the accumulation of mineral N is significantly suppressed by every crop, and only insignificant and short periods of relatively high concentration are left in late spring and early fall. A typical example hereof from data collected by the authors on a heavy loam soil in Holland in 1938 is shown in Fig. 1.

4. The winter minimum was unanimously ascribed to the heavy leaching in humid climates, and the process of mineralization also appeared hampered by low temperatures. The rapid rise in the spring was recognized as a result of the "partial sterilization" effect of frost

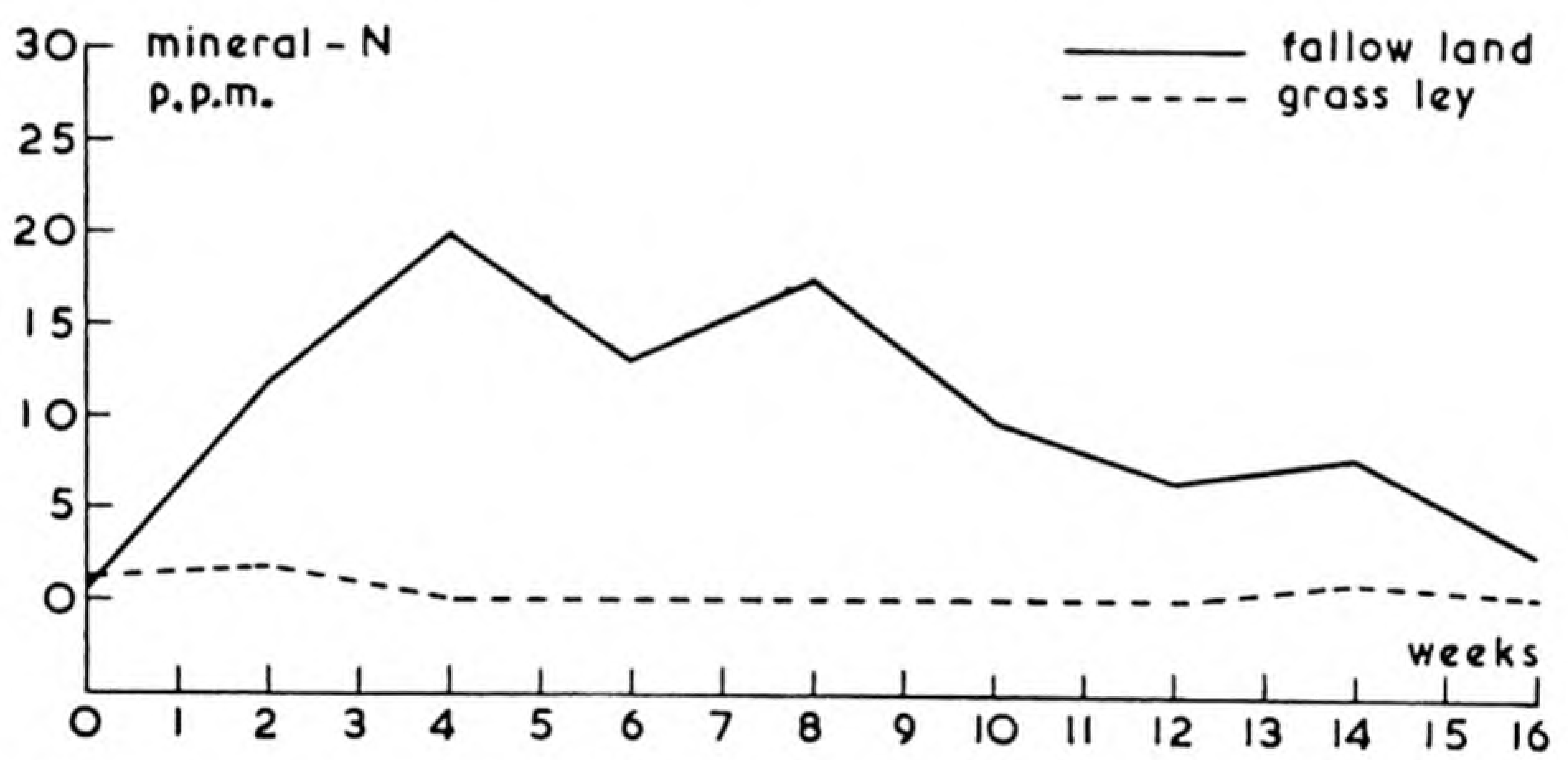

FIG. 1. Mineral nitrogen content in a clay soil on fallow and cropped parts of the land from May to August inclusive.

on the soil, and the depression during the development of the crops already was understood to be a double action of the uptake of the available nitrogen by plants and of the fixation of it by microbes developing in the rhizosphere because of carbonaceous substances excreted by the plant roots or of decaying residues of rootcaps, root hairs, etc.

5. Under perennial crops, especially under a grasscover, the mineral N content remains very low during the whole year, and even high applications of mineral nitrogen are rapidly absorbed. So it was long ago understood that the conditions in grassland are favorable for a fixation of all available nitrogen by microbes as insoluble organic compounds. A very clear presentation of experiments leading to this conclusion is given by Bizzell (1922). To this synthesis of humus in forest and pasture land the generally observed build-up of humus and of potential fertility in virgin land and in permanent grassland was attributed as long ago as 1889, in contrast to the more or less rapid degradation of it in arable land (Lawes, 1889).

6. The C:N ratio in organic matter added to the soil is of primary importance to the course of mineralization; only material with a C:N ratio of 20:1 or lower generally can directly provide mineral nitrogen; material with higher C:N ratios initially allows only the liberation of CO_2, all mineralized nitrogen being immediately again bound in the protoplasm of the developing microbes. A lag period therefore must be expected until the C:N ratio is narrowed to 20:1 or thereabouts. This whole complex phenomenon is based on two suppositions: (1) during the microbial decomposition of organic matter at least 1.5 to 2.5 per cent N must be present in that matter to guarantee good growth of the microbes without absorption of nitrogen from the surrounding medium; and (2) the nitrogen content of the decomposing material tends on the long run to approach that of the protoplasm of the microbes. The most important of the older publications on this subject may be cited: Waksman and Tenney (1927); Waksman (1932); Sievers and Holtz (1926); Jensen (1929); Lemmermann *et al.* (1930).

Not only were the above general conclusions developed in the older publications, but also some practical consequences thereof were formulated and extensive quantitative data were collected. The dominant effect of leaching by rainfall especially during the winter was fully recognized (Russell, 1914; Crowther and Mirchandani, 1931), and for light permeable soils in the rainy climate of England it was shown by Crowther and Mirchandani (1931) and more recently by T. W. Barnes (1950) that the NO_3 content remains very low throughout the whole season, i.e., below 4 p.p.m. calculated on dry soil. However in less permeable and heavier soils much higher mineral N contents have been reported, in heavy loams in spring as much as 20 p.p.m. and in some exceptional cases even 50 p.p.m. (Russell, 1914); in peaty soils even much higher concentrations of mineral N, up to 500 p.p.m., were observed in spring in the field (Rheinwald, 1933).

The above short statements are sufficiently indicative of the fact that the study of the general course of the mineralization of organic nitrogen in soil was practically completed before 1935. Consequently not many papers dealing with these fundamental problems have been published since that date, although it is surprising that many of the modern publications still consider it worth while to mention parenthetically observations dealing with these old and entirely solved problems. In the subsequent paragraphs modern publications dealing with several problems will be discussed, but the numerous statements about questions no longer urgent will be disregarded, only new problems being taken into consideration. A short but critical and illuminating review entitled: "Availability of organic nitrogen and phosphorus from plant residues,

manure, and soil organic matter," was recently given at the Soil Microbiology Conference (Purdue University, June, 1954) by Bartholomew.

1. Mineralization of Nitrogen from Native Humus in Arable Land

First of all some papers dealing with the effect of temperature and moisture on the whole process of nitrogen mineralization or on some phases thereof must be mentioned. Feher and Frank (1937) determined the optimal temperature and moisture for the nitrification process. They found for their conditions 30° to 35° C. and *circa* 30 per cent moisture by weight to represent optimal conditions. In 1942 Gerretsen again made an elaborate study in pot experiments of the influence of temperature on nitrification and on the whole process of mineralization of nitrogen. He could demonstrate that even very low temperatures permit active mineralization: 5° C. provided for complete nitrification, even of high applications of $(NH_4)_2SO_4$, within two weeks. Ammonification and the reverse fixation of mineral nitrogen both proved to be active even at temperatures between 0° and 5° C. But these results may not be regarded as in disagreement with the older and generally accepted opinion that the higher the temperature, the faster the process of mineralization. This general rule has been recognized by Jenny (1928, 1929, 1930, 1931, 1941) as the reason for the fact that colder climates generally are characterized by soils of higher humus content and consequently also of higher N content. Within one climatic type he claims an increase in C_t and N_t of about 2 to 3 times for every 10° C. decrease in average temperature.

Another group of papers that must be mentioned here are those dealing with the recovery of applied nitrogenous fertilizers. Black *et al.* (1947) have presented the results of their determinations of recovery of applied and mineralized nitrogen in crops. The more nitrogen was available for the plants, the lower was the percentage of recovery, decreasing from *circa* 57 per cent with 32 pounds of N per acre to only about 28 per cent with 128 pounds of N per acre. Bartholomew *et al.* (1950) also found that a large part of fertilizer nitrogen applied became immobilized in the soil organic matter, and was not absorbed by the crops. Similar results were also reported by Hiltbold *et al.* (1951), Iversen and Dorph-Peterson (1951), and Bartholomew and Hiltbold (1952). In all these investigations the old experience was also confirmed, that in uncropped land in most cases no fertilizer nitrogen became immobilized in the organic substance of the soil, or this immobilization was only temporary, whereas always in cropped soils a

considerable part of the applied mineral nitrogen could not be accounted for in leachings, volatilization, and uptake by the crop, apparently being fixed as organic nitrogen in microbial proteins. A very careful investigation of this fixation of mineral nitrogen in the rhizosphere with the same conclusion has also been performed by Gerretsen (1950).

Thompson and Black (1950) studied the relation between the rate of mineralization of nitrogen, carbon, and phosphorus from organic substances in some Iowa soils. This relation proved to be very close for N and C. Virgin soils mineralized much more N, C, and P than did cultivated soils. The writers therefore concluded that the organic substances apparently became more resistant to mineralization as the degree of decomposition advanced. They also determined the percentage of total N that became mineralized within a certain period.

An interesting publication appeared recently in Annales Agronomiques (Soubiès *et al.*, 1952) on the process of the downward movement of accumulated mineral N during the wet season. They could by repeatedly taking small samples from centimeter to centimeter in the profile follow the mineral N carried downward by the rain. In a permeable sandy soil under the conditions of the moderately humid climate of southern France this mineral N proved to migrate as a sharp wave, being moved down an average of 1 cm. by every 3 to 4 mm. of rainfall. Though this study may not be generalized, as it was performed in a soil with a pronounced accumulation of mineral N in the extreme upper layer, it gives some valuable information on the mechanism of leaching of mineral N in rainy periods.

Other recent publications on the subject of movement of mineral N in soil under influences of rainfall or drought are the papers of Benson and Barnette (1939), of Conrad (1940), and of Jones (1942). They all agree that nitrates remain practically unabsorbed and consequently are readily leached even by moderate rainfall, whereas ammonia-N is strongly retained by absorption especially in heavy soils. Krantz *et al.* (1944) confirmed these results, but their work is remarkable in that they reported only very slow nitrification of added $(NH_4)_2SO_4$ and the amount of leaching also is insignificant. Apparently precipitation was so low in their experiments that neither washing out of soluble substances nor nitrification was comparable with corresponding values in a more humid climate. Spectacular figures for losses of N by leaching in a humid climate have recently been given by Baumann and Schendel (1952) and by Lehr and Veen (1952). The latter paper reports very significant leaching of mineralized nitrogen during the winter season in permeable sandy soils in the humid climate of Holland. The effect of this leaching is considered to be the main factor determining the yield

of rye; a highly significant negative correlation ($r = -0.419$) could be found between rye yields and the precipitation during the preceding winter months.

A related subject is the effect of oxygenation on nitrification. As long ago as in the time of Schloesing it was known that nitrification requires oxygen, and a recent exact study of the relation between the oxygen pressure in the atmosphere and the nitrification in the soil has been performed by Amer and Bartholomew (1951), who confirmed the view that nitrification is a strictly aerobic process.

This result, however, should not be confused with the effect of aeration on the whole process of mineralization, since the first stages—ammonification—are not necessarily aerobic processes, and therefore the nitrogen nutrition of plants is not necessarily reduced under anaerobic conditions. However, it must be recollected that the oxygenation of the soil is a very complex problem depending not only on the water content and the compactness of the soil, but also on its content of mineralizable organic matter and of other reduction-oxidation systems. Disregarding some of these factors must be assumed to be the reason for the divergent results of different experiments on the effect of the soil moisture content on the mineralization of nitrogen. Many investigators, even long ago (Schloesing and Müntz, 1877–1878; Dehérain, 1902; Traaen, 1916; Stevens and Withers, 1910) reported unhampered ammonification and even nitrification in soils with very high water content, up to nearly complete waterlogging. Recently similar results have been reported by Pikovs'kaya (1940) and by Lees and Quastel in all of their papers. The investigators arriving at these results generally used permeable soils with not too much readily oxidizable organic matter and presumably with an adequate redox-buffering capacity, and with sufficient movement of the moisture in the soil. Contrary to such investigations in many papers, both old and modern—using other types of soil and other experimental conditions—very high sensitivity to reduced oxygenation was reported, sometimes even of the ammonification process (Jones, 1932). Interesting results have been presented by Smith and Cook (1947) on the influence of the degree of water saturation, of more or less compaction of the soil, and of more or less artificial aeration in a pot experiment with sugar beets as test-crop. In this experiment chopped maize, lucerne, or sweet clover were mixed with the soil. With additions of fresh plant materials, this soil showed a high sensitivity to any means of reduction of the oxygenation. Not only did the development of the sugar beets prove to be adversely influenced thereby, but also it was possible to show a marked retardation of the formation of mineral nitrogen in all pots with reduced oxidations.

A question about the decomposition of humus in soil, throwing a new light upon the stability of the native humus, that still is hotly discussed, was presented in a series of papers by Norman and collaborators (Norman and Werkman, 1943; Broadbent and Norman, 1947; Broadbent, 1948; Broadbent and Bartholomew, 1949; Thornton, 1946).

This approach seems to initiate an entirely new and promising avenue of research on the formation and decomposition of humus. These investigators studied the influence of fresh organic matter on the decomposition of the consolidated humus in the soil, applying the modern technique of isotopically labeled carbon and nitrogen. Löhnis, as long ago as 1926, had already claimed a significant acceleration of this decomposition by the addition of fresh green manure to the soil. They succeeded in confirming the statement of Löhnis and demonstrated a significant stimulation of the decomposition of the "stable" humus by fresh organic matter during the first period after the addition of the latter. Their conclusion is therefore that the "stable" humus is much less stable than generally is supposed and that its decomposition is retarded only by lack of an active microflora. They speak about the freshly added matter as "a forced draft on the smoldering bacterial fire."

It is not the intention to deal here in full with this problem, nor to discuss the explanation given by Norman and collaborators, as this subject lies partly outside the scope of the nitrogen mineralization topic. Broadbent (1948) concluded that this effect of fresh organic matter sometimes can even bring about a net decrease in soil organic matter, especially if small amounts of readily decomposable material are added frequently to the soil. This last conclusion was confirmed in 1953 by Hallam and by Hallam and Bartholomew, who also found that small amounts of fresh organic matter destroyed more of the stable humus than they added through the synthesis of new stable humus, whereas larger additions of fresh material brought about a net gain in stable organic matter of the soil.

A critical study of this problem has also been performed by Bingeman *et al.* (1953), who fundamentally could confirm the findings of Norman and collaborators, but quantitatively found the "priming" effect of the fresh additives in their experiments to be scarcely significant and not always reproducible. Besides, they encountered many technical difficulties in experimental work with the tracers, whereby they arrived at the conclusion that many more experiments would be needed before this whole problem could be accepted as definitely solved, the more so since they got different CO_2 productions from equivalent amounts of labeled and not labeled material, thereby again bringing

into discussion the question as to whether radioactive substances influence microbial life.

The above-mentioned observations of Norman and collaborators on the stimulation of the decomposition of stable humus by fresh organic substances raised the question as to whether plant roots, with their accompanying excretions, and dense microbial population in the rhizosphere might not also accelerate the breakdown of the stable humus in soil. This effect, of course, could be presumed to be obscured by the well-known synthesis of fresh organic substances by the rhizosphere microbes using the soluble root excretions and mineral nitrogen in the soil, but at the same time an increased attack on the stable humus might be possible, though the net result is a decrease of the total mineralization of organic substances in the soil by cropping the land. A careful study of Bartholomew and Clark (1950a, b), using the stable isotope N^{15}, indeed revealed a considerably faster breakdown of the stable humus in cropped as compared with uncropped land; this effect, however, was overcompensated by the above-mentioned synthesis of microbial cells in the rhizosphere.

2. *Mineralization of Nitrogen in Grassland*

The general character of the nitrogen balance in grassland has been investigated long ago, as was mentioned in paragraph 5 on page 303, but the spectacular ability of perennial grass to absorb even very high amounts of applied nitrogen and to retain nearly all mineralized and added nitrogen in organically bound form, is still considered to be surprising, even in recent years. Consequently, much attention still is paid to this characteristic of grassland, and the whole problem of nitrogen mineralization in grassland remains unsolved.

Modern publications reporting clear-cut examples of very low mineralization of nitrogen in grassland are primarily from areas with humid climates: Lyon and Bizzell (1936), Bizzell (1944), Stevenson and Chase (1953), Stöckli (1949), and especially Richardson (1938) in his clear and elaborate treatise on the nitrogen cycle in grassland soils at Rothamsted. In arid climates similar observations were described by Newton *et al.* (1939a, b), Rhoades and Newell (1946), Prescott (1934), Penman (1949), Cornish (1949), and especially Theron (1951) and Theron and Haylett (1953).

All these papers, as well as numerous publications in earlier years, proved that in all climates the mineral N content of grassland was much lower than in comparable arable land. In most cases only small amounts of mineralized nitrogen could be demonstrated; it is most remarkable that this low level is in most cases maintained during the whole year

even in periods when no growth of grass takes place. Very illuminating figures are given by Richardson (1938) in the graphs, Figs. 1 and 3 accompanying his paper, where it can be seen that on plots without any N fertilizer the NH_4-N content fluctuated between 2 and 8 p.p.m. and the amount of NO_3-N between zero and 2 p.p.m., while $(NH_4)_2SO_4$ added as 50 p.p.m. became entirely absorbed within several days or at most a fortnight. Similar data can be found also in the other communications mentioned.

Some exceptions were reported from soils very rich in nitrogenous organic substances, such as peat, especially when abundantly limed (Reincke, 1930, 1932; Rappe, 1950), or in humid tropical or subtropical climates (Parbery, 1945; Hardy, 1946), but even then only temporarily slightly higher concentrations of mineral nitrogen were found.

A situation similar to that in permanent grassland also prevails in forest soils, and generally under all types of permanent and undisturbed vegetation (Süchting, 1949; Michniewicz, 1951; and numerous earlier papers of Romell, Lundegårdh, and others). However, recently a striking exception has been reported by Jenny *et al.* (1949) and Jenny (1950) for the soil in humid-tropical forests of Columbia. There he found soils very rich in total humus and total nitrogen, and with strong mineralization and consequently a rather high level of mineral nitrogen. But Jenny himself likes to ascribe this situation to an exceptionally high percentage of leguminous trees in those forests.

In summary, we can conclude that the fact that there is a much lower accumulation of mineral nitrogen in grassland than in arable land has been sufficiently proved, but several divergent explanations of this phenomenon have been offered. One of the reasons presumably is an underestimation of the formation of roots and residues in grass leys and perennial leguminous crops. The older data on the production of roots and residues by crops were obtained with the use of inadequate techniques. Really critical and reliable figures, however, have been collected in recent years by Goedewaagen and Schuurman (1950), by Freckmann (1949), by Goring and Clark (1949), and especially in the very careful and extensive study of Köhnlein and Vetter (1953a). It is evident from these figures that the production of residues in grassland is much higher than under any arable crop. During the first year grass leys, clover-grass mixtures, and also clover- or lucerne-leys produce about 2500 to 3000 kg. per hectare roots and residues; cereals do not leave more than 1200 to 1500 kg. per hectare; leguminous arable crops (peas, beans, etc.) produce 500 to 2000 kg. per hectare; and beets and mangolds, only 600 to 1000 kg. per hectare. These figures, however, are not entirely comparable so far as the nitrogen balance is

concerned, since they represent the amount of residues at the time of harvest, when all annual crops are already ripe and nearly dead and consequently have already considerably decreased their root system. Cereals proved to have lost by that time 60 to 70 per cent of their maximal root-mass (Goedewaagen and Schuurman, 1950; Schultze, 1912–1914), whereas the perennial plants then just approach their optimal first-year development. The formation of roots and residues in clovers and grass leys may be assumed to be considerably higher in their first year than that of annual crops. However, there are still no exact data on the formation of new roots and residues by grassland in subsequent years. The modern data (Köhnlein and Vetter, 1953a) show a gradual further increase in the total amount of roots and stubble, leading finally to the well-known high accumulation of living and dead roots and residues and humus characteristics of perennial grassland. But the annual increase, if averaged over the years of observation, results in a rather low annual increment. Of course, the annual turnover in plant material is much higher than the net annual increases, but the pronounced retention of all nitrogen in grassland soils can be explained only on the following basis. In the long run an equilibrium must be reached, with nearly as much nitrogen mineralized as has been added to the soil as fertilizer and as manure and fixed from the atmosphere; otherwise an infinite build-up of humus and accumulation of organically bound nitrogen would occur in permanent grassland. Fundamentally the supposition of an infinite accumulation is unreasonable, but the formation of stable genuine humus in the grassland mat from the accumulated, only partly decayed, residues as a result of retarded decomposition, typical for all grasslands, is a slow process, and old permanent grasslands and prairies contain very much accumulated humus with a high N content. Thus a grassland through many decades can retain all mineral nitrogen, thereby giving the impression that it possesses this ability infinitely.

One of the consequences of the accumulated organic residues at all stages of decomposition in grasslands is their function as buffer for temporary absorption of any occasional addition of nitrogen fertilizer, thereby again giving the impression of an unlimited ability to fix mineral nitrogen.

A specific trend retarding the decomposition of plant residues and at the same time forming stable humus abundantly, has recently been proposed as typical for the surface layer of any undisturbed soil, both grassland and forest (Harmsen, 1951). This theory is based on the consideration that the accumulation of humus in grassland cannot entirely be explained by the generally higher amount of plant residues produced in grassland and forest than in arable land, because even the scantiest

below 3 p.p.m. and never rising above 9 p.p.m. (expressed as N). Even heavy applications of ammonium sulfate were nearly instantaneously absorbed and were reduced to the same level of 3 to 9 p.p.m. that was characteristic and uniform for all treatments studied (unmanured, organic manure, minerals, nitrates, or ammonium sulfate). This behavior seems to point to a factor prohibiting the absorption of the last traces of NH_4-N by plants or microbes—a rather improbable proposition if one considers the NH_4 content to be an equilibrium between the formation and the removal of NH_4. Of course another explanation also is possible, though it never has been formulated in the literature, that is, that all methods of analysis applied split off a certain amount of ammonia nitrogen from the accumulated but not yet decomposed organic substances. As practically all investigators determined the NH_4-N by distillation with magnesia, and used extracts of soil samples prepared with diluted solutions of electrolytes, it must be assumed that some organic substances are soluble in such extracts and are decomposed during distillation with liberation of NH_4 groups, although they still were unavailable to plants and microbes and even to the nitrifying organisms. Should this hypothesis be proved, then the constant minimum amount of NH_4 in grassland soils will no more be of any importance, being recognized as an artifact.

Some investigators proposed yet another explanation, that is, direct suppression of the nitrification process by living plant roots. The first to express this idea were Lyon and Bizzell in 1918, but in their later publications (Lyon and Wilson, 1921; Bizzell, 1922, 1944; Lyon *et al.*, 1923, 1930; Lyon and Bizzell, 1936) this explanation was mentioned only once (Lyon, 1930). In 1929 Starkey also considered the possibility of such a direct adverse effect of living roots on nitrification. Moreover, Theron (1951) and Theron and Haylett (1953) recently again proposed this explanation. They do not restrict this suppression to grass roots, but claim that all living roots exert the same influence on nitrification, and it depends only on the mass of roots whether the phenomenon becomes more or less apparent. Therefore a really spectacular effect can only be observed in older (perennial) grassland.

A complete explanation of the adverse effect of living plant roots on nitrification is not given by Theron, but as a possible way of accounting for it he suggests the action of some organic excretions from the roots, and assumes that the nitrifying organisms are very sensitive to soluble organic matter. This last assumption, however, is open to criticism, as during the last decades more and more evidence has been collected showing that nitrification is not necessarily retarded by organic substances (Jensen, 1950a, b; Meiklejohn, 1951, 1952, 1953;

Kingma-Boltjes, 1935; Quastel and Scholefield, 1949; Lees, 1947; Murray, 1923; Hes, 1937; Fred and Davenport, 1921; Barritt, 1933; Engel, 1932, 1934), and some strains of nitrifying organisms thrive and nitrify actively even in media rich in soluble organic substances (Jensen, 1950a, b). In addition to this hypothetical explanation, Theron cited the following evidence in support of this theory:

1. The amount of organic matter excreted by living roots, and consequently immediately available near all young living roots, had to be improbably high to account for all NO_3 being directly bound again by microbes attacking these excretion products.

However, estimating these quantities, Theron seems to consider all mineral N to be absorbed exclusively by root excretion. Exact measurements of organic substances given off by living roots to soil under natural conditions never have been made, but the effect of excretions on the microbes—the so-called "rhizosphere effect"—has been extensively studied. The most elaborate contributions were given by Starkey and Krasilnikov and in recent years by Lochhead and associates in different papers (Starkey, 1929a, b, 1931a, b; Krasilnikov, 1934; Krasilnikov *et al.*, 1936a, b; Lochhead, 1940; Katznelson and Richardson, 1943; Timonin, 1940). They all found many more microbes around the roots than in the rest of the soil. Short-term fluctuations of readily hydrolyzable organic carbon are also reported and explained in the publications of Sauerlandt and Groetzner (1953a, b).

2. It is a general observation that accumulation of NO_3 in arable land is resumed practically directly after the harvest of the crop, consequently at a time when many dead roots and other fresh plant residues are available in the soil. Yet these dead substances cannot suppress the NO_3 formation, whereas the living roots could.

This argument, however, also can be criticized by recollecting that the accumulation of NO_3 is a result of an equilibrium between formation and consumption, and after ripening of the crop the uptake by the plants stops. Besides that, the resumption of the NO_3 accumulation after harvest is in most cases very slow.

3. Theron found in his experiments even during the winter a complete suppression of NO_3 accumulation in spite of the living but dormant state of the grass roots at that time. He recognizes herein proof that it is not absorption of the liberated nitrate by the roots or by the microbes that is involved, but a suppressive effect on nitrate formation on the part of the living roots, even during a period of growth inactivity.

This argument, however, again cannot be accepted as strong proof, since Theron made his observations in the summer-rainfall region of South Africa, where the soil during the winter may be too dry for any

bacterial activity, and consequently also for the mineralization of organic nitrogen. In any case the theory of Theron can scarcely be considered to be of general validity, especially since it does not explain the characteristic constancy of the NH_4 level.

All the above-mentioned characteristics of permanent grassland require at least a couple of years to become fully developed. During the first years young grass leys still behave partly as arable land, though land having an exceptionally high production of roots and residues. A detailed recent study of the gradual changes in the nitrogen status of a grass ley during 8 years, after 17 years of arable cropping, can be found in the paper of Theron and Haylett (1953). The conditions of real grassland became established only after 3 to 4 years. Other papers describing this process of gradual changes in the nitrogen status of young grassland are: Bizzell (1944), Richardson (1938), R. Newton *et al.* (1939), J. D. Newton *et al.* (1939), Penman (1949), Eggleton (1935a, b), Parbery (1945).

3. *Mineralization of Nitrogen under "Abnormal" Conditions*

It is definitely a shortcoming that the transformations of nitrogen have been studied almost exclusively under conditions of temperate climate, because it is just the more or less abnormal and extreme conditions that can often demonstrate some characteristic phenomena in the most clear-cut way. Fortunately some work, often incidental, has been done under various special conditions. The modern papers will be briefly mentioned here.

a. Peat Soils. Investigations on nitrogen mineralization in uncultivated virgin bogs are very scarce. Cyplenkin and Schilin (1936) showed NO_3-N formation in the waterlogged peaty soil of the tundra only locally on some hill crests and southbound slopes. Ammonification was much more common in the tundra soil, but still was very slow, compared with well-drained neutral soils. Michniewicz (1951) determined the rate of nitrogen mineralization and the number of nitrifying organisms in the upper layers of the forest floor and of peat bogs. She also found only very slow and irregular nitrification in all water-saturated or acid soils, but much more active nitrification in the forest floor and litter of deciduous forests.

More work has been devoted to reclaimed and cultivated peaty soils. Earlier investigators found that in these soils a rather strong and rapid decomposition of the organic matter took place with a corresponding liberation of large amounts of mineral nitrogen. However, without liming, the pH of peaty soils is often too low for vigorous NO_3 formation, but ammonification practically always proves to be high. In 1950

Rappe published his work on seasonal variation in the mineral nitrogen of a sphagnum-peat soil. He again found vigorous mineralization in incubation tests; in 21 days about 140 p.p.m. of nitrogen was liberated. In comparisons of cropped and fallow plots the same differences could be found as in ordinary clay or sandy soils, but the exhaustion of the mineral nitrogen by the crop and the microbes during the summer season was slower and less complete.

In 1938 Mork studied the mineralization of nitrogen and nitrification in forest and peat soils in Norway. He was especially interested in the temperature range of vigorous mineralization. The extreme temperature limits for nitrification in these soils proved to be 4° and 40° C., with the optimum found to be between 20° and 30° C.; this is about the same as in ordinary soils.

A very extensive study was published by Kaila *et al.* (1953) using two acid peat soils with pH of about 4.7 and with 350 p.p.m. mineral N at the time of sampling. In incubation experiments very high amounts of nitrogen became mineralized, at 20° C. 780 p.p.m. and at 35° C. as much as 1400 p.p.m. in three months. At 65° C. even more nitrogen became mineralized, but that process might have been a chemical hydrolysis. This very strong mineralization stopped entirely at the ammonia stage, while NO_3 formation was very slow even after liming to pH 6.0. The influence of liming was surprisingly small also on the ammonification. The mineralization figures of Kaila *et al.* (1953) are, however, not directly comparable with those of other authors, since these incubation experiments were done with dried, ground, and remoistened samples and it is generally accepted that drying and remoistening a soil sample, and especially a peat sample, stimulates its decomposition. The observation of Kaila *et al.* (1953) that about 5 per cent of the total nitrogen of the peat soils was soluble in water, is of general importance, since in ordinary soils only a negligible part of the total nitrogen is water-soluble. Interesting also is the observation that in peat soils more carbon became mineralized than nitrogen, with the consequence of a gradually decreasing C:N ratio.

b. Irrigated Soils. Irrigation in semiarid temperate climates was long ago recognized to be similar to rainfall in its effects, decreasing the accumulation of mineral nitrogen by leaching (see, for instance, the extensive paper of Greaves *et al.*, 1917). But in extreme arid tropical climates the situation is entirely different; without irrigation no leaching by rain occurs, and the temperature sometimes is far above the optimal for microbiological processes. Therefore evaporation reaches the highest possible level, and the entire supply of water in the soil moves up and down at every flooding and subsequent period of evap-

oration. Very irregular variations in the mineral N content are the result of these conditons, with rapid movement of the soluble nitrogen vertically and horizontally through the soil. A characteristic feature is the accumulation of soluble nitrogen (mainly NO_3-N) in the upper layer of the soil and especially in all unflooded elevated spots (ridges along the ditches, etc.) in soils with a bad structure and a high content of electrolytes, as already shown by Prescott (1919, 1920a) in Egypt. Similar observations can sometimes even be made in arid temperate climates especially under fallow conditions. Headden (1913), Stewart and Peterson (1914, 1917), and Doughty *et al.* (1954b) even reported such observations on unirrigated land. It will be clear that scarcely any regularity can be expected in the variations of mineral nitrogen in such soils. Therefore it is not surprising that Jewitt (1945), studying the nitrogen requirement of Sudan Gezira soils (heavy clay with a high content of electrolytes, a pH of 9.0 to 9.5, and a poor permeability) with a pronounced response to fertilization with nitrogen, could not demonstrate a regular and rapid total exhaustion of the mineral N at any time in the growing season. The mineral N content varied between 5 and 20 p.p.m. in the irrigated fields, mainly as NO_3. In incubation experiments the nitrogen mineralized was about 20 p.p.m. in five weeks. This observation is not in agreement with some older reports on the mineralization of nitrogen in irrigated soils of tropical regions. Prescott (1919, 1920a) obtained in three months of incubation as much as 240 p.p.m. of mineral nitrogen; but it may not be forgotten that Prescott's observations refer to rather well-drained soils of the Nile, whereas Jewitt (1945) was dealing with alkali soils with stagnant water in deeper layers.

c. Unirrigated Tropical Soils. Though the literature about nitrogen mineralization in tropical soils is still rather meager, some careful and extensive work was performed long ago (Burt and Leather, 1909; Leather, 1911) in which some characteristic aspects of the nitrogen balance under tropical conditions were elucidated. Owing to the high temperature, all biochemical processes are generally accelerated; consequently ammonification and nitrification both are very active, if no adverse influences check this activity. Lack of moisture during the dry season and sometimes too high temperatures in bare soil may suppress mineralization. Periods of drought often also bring about an accumulation of electrolytes and a rise of the pH to unfavorable levels. During the wet season, on the other hand, the rainfall is so superfluous that even vigorous mineralization is insufficient to prevent the decrease of the mineral N content to nearly zero. Much nitrogen is lost to the subsoil. The changes of the mineral nitrogen content in soils of the

tropical zone with pronounced wet and dry seasons therefore resemble the situation in soils with seasonal irrigation, as in Egypt (Prescott, 1920b).

Some recent papers confirmed the above outlined course of nitrogen mineralization. A very high rate of mineralization has been found by Griffith and Manning (1950), Hardy (1946), Dhar and Mukherji (1936a, b), Jenny (1950), and Jenny *et al.* (1949). Griffith observed accumulations of NO_3-N up to 500 p.p.m. in Uganda soils in Africa, and Dhar and Mukherji reported even higher amounts for fertile soils in India. The latter writers claim that 10 to 48 per cent of the total N of these soils can be water-soluble mineral nitrogen. It seems rather difficult to explain how in soils with a more or less normal moisture regime such high contents of mineral nitrogen can be formed without complete exhaustion of all organic nitrogen in a few years. Only by assuming a very dry climate, practically without leaching by precipitation, or a temporary accumulation of soluble ions in the surface layer of the soil by capillary rise and evaporation can one find acceptable this explanation of the figures reported. However, Dhar and his collaborators (Dhar, 1935, 1938a; Rao and Dhar, 1931a, b, 1934; Dhar *et al.*, 1933, 1937; Dhar and Rao, 1933; Dhar and Tandon, 1936; Dhar and Mukherji, 1936a, b; Dhar and Plant, 1944; Dhar and Seshacharyulu, 1939; Rao, 1934) try to reach an adequate explanation solely by taking into account the very high rate of bacterial mineralization at the high temperature in tropical countries and a chemical mineralization process induced by the direct irradiation of the soil by sunlight. The direct effect of the sunlight as well as high temperature is said to be responsible for the activation of this chemical process, which remains unobserved in temperate climate. This old hypothesis (Russell and Smith, 1906) of a chemical mineralization of organic nitrogen, later revised by Rao and Dhar, still deserves more checking and more study, before it can be accepted as proved, the more so since some investigators have failed to find high rates of nitrogen mineralization in tropical countries (Jewitt, 1945, 1950). Also critical studies of Winogradsky (1935), Fraps and Sterges (1935), Waksman and Madhok (1937), and recently Joshi and Biswas (1948) have collected much evidence that the photochemical nitrification in soil is not important, even under the conditions in India. This whole subject has recently been amply reviewed by Meiklejohn (1953).

The depressive effect of desiccation of the soil during the dry season has recently been confirmed by Jewitt (1945, 1950) and by Griffith and Manning (1950). They observed complete interruption of the mineralization in the dry and sun-scorched bare soils during the dry

part of the year. The formation of nitrates in some tropical soils and in some arid soils of the temperate climate can be suppressed by too high alkalinity as well as by drought. However, this subject will be discussed on pages 345–346. Here it must be pointed out that only the last phase in the mineralization of nitrogen, the nitrification step, is affected by high pH values, whereas the ammonification process proceeds normally at much higher pH values. A good review of this subject is given by Martin *et al.* (1943).

Spectacular observations of heavy leaching of the mineral nitrogen during the monsoon have been reported by Jewitt (1945, 1950) for the Sudan, by Griffith and Manning (1950) for Uganda, by Hardy (1946) for British West Indies, and by Dhar with collaborators in different papers for India (Dhar, 1938b, 1943, 1947a, b; Dhar *et al.*, 1934; Dhar and Mukherji, 1935, 1936a, b, 1938; Dhar and Seshacharyulu, 1936; Dhar and Plant, 1944). The school of Dhar claims in most of these papers a significant sparing effect of carbohydrates on the loss of nitrogen by leaching and emphasizes the application of organic wastes with a wide C:N ratio and of catch crops during the wet season. Hardy (1946) and Griffith and Manning (1950) support this advice. This conception is in agreement with the quick decomposition of organic matter in Indian soils, resulting in a rapid narrowing of the C:N ratio, as claimed by Dhar, and also supported by Hardy. If this conception of the nitrogen and humus balance should be proved, then tropical conditions should require the application of organic manures with a much wider C:N ratio than can be used in temperate climates. However, Jewitt (1945) observed in the alkali soils of the Sudan just the reverse situation, namely, that addition of carbonaceous material reduced immediately the mineral N content. Interesting is the observation of Griffith and Manning (1950) that during the rainy period the NO_3 still accumulated in unprotected bare soil, where the evaporation apparently balanced the downward movement due to precipitation, whereas on mulched plots with a reduction of evaporation the NO_3 content was significantly decreased during the monsoon.

In the poorly drained impermeable alkali Gezira soils in the Sudan the leaching of the nitrate stopped at a depth of 1 or 2 feet, and at that level an accumulation of NO_3 was observed (Jewitt, 1950).

In some of their papers Dhar and collaborators also presented their theory of the nonbiological (chemical) fixation of atmospheric nitrogen in soil at high temperatures and sunshine.

d. Rice Fields (*Sawahs or Paddy Fields*). The special conditions prevailing in rice fields, when flooded for some months, are responsible for a complete suppression of nitrate formation; even added nitrate is

rapidly reduced. However, the ammonification was found to be almost normal in these entirely waterlogged anaerobic soils, giving high amounts of mineral N at the beginning of the growing season, followed by an exhaustion of it during optimal growth of the crop. After the harvest of the rice and draining of the water, the nitrification soon recovers to a normal level. The prolonged maintenance of anaerobic conditions apparently does not destroy the nitrifying organisms. All the above facts were already recognized many years ago. Older studies of the nitrogen transformation in sawahs are: Gerretsen (1921); Kapp (1933); Sreenivasan and Subrahmanjan (1934, 1935). In recent years only a few papers dealing with this type of soil have been issued. Both Bamji (1938) and Bhuiyan (1949) presented many quantitative data about the amounts and transformation of different forms of nitrogen. The older interpretation was confirmed by these investigators, with the exception of the fact that the concentration of ammonia was found to remain rather high during the whole growth period; Bamji (1938) found 17 to 59 p.p.m. NH_4-N, suggesting a higher rate of ammonification than of uptake by the rice and no leaching in the stagnant water of the sawahs. But Reed and Sturgis (1937, 1939) could not confirm the results of Bamji (1938). They found in rice fields during the growing season nearly an entire exhaustion of all forms of available nitrogen, and Reed and Sturgis (1937) observed a significant response of rice to N fertilization. Similar results have also been attained by Willis and Sturgis (1945, 1944–1945) and by Willis and Green (1949).

A peculiar problem arose about the maintenance of N in rice field soils. It was observed that a moderate fertility was maintained for many years or even centuries in the sawahs, even without any intentional fertilization with N, and that the N content of the flooding water proved not to be enough to explain this fact. Therefore numerous investigators tried to find the mechanism of N fixation in rice fields. Several different hypotheses have been proposed. One of the theories has been advocated by Rao and Dhar, who claim that in tropical conditions N may be fixed photochemically without microbes taking part in the process (Rao and Dhar, 1931a, b, 1934; Dhar and Rao, 1933). The conditions in rice fields were claimed to be exceptionally favorable for this photochemical N fixation. Other workers considered different algae or blue-green algae to be responsible for the marked N fixation in paddy fields (Allison and Morris, 1930; Singh, 1939, 1942; Bhaskaran and Pillai, 1942; Kamen and Gest, 1949). But this theory was not accepted by other investigators (Stokes, 1940; Fogg, 1942; Willis and Green, 1949), and many aspects remain obscure. A third view, which is gain-

ing more and more support and which seems to be the most correct interpretation of the problem, stresses the role of N-fixing bacteria in the flooded soils (Sen, 1929; Uppal *et al.*, 1939; De and Pain, 1936; Chaudhuri, 1940). Recently this problem became much more clearly elucidated by the work of Starkey and De (1939), Starkey (1939), and Derx (1950a, b, 1951), who isolated from wet tropical soils and from waters new species of *Azotobacter* and a new genus of N-fixing bacteria—*Beyerinckia*—widely distributed in all types of soil and water in the humid tropics, and actively fixing atmospheric N. Derx considers it very probable that Altson in 1936 and Groenewege in 1913 had already isolated and described the *Beyerinckia* species. It, therefore, can now be accepted as proved that flooded cultivated soils under tropical climatic conditions fix very high amounts of atmospheric N. Even more can be gained thereby than is removed by the crop or lost by volatilization, in spite of the fact that in the generally alkaline paddy soils much NH_4 is lost as gas to the atmosphere, as was shown by Sreenivasan and Subrahmanyan (1934, 1935), while other workers found volatilization of N_2 and N_2O the main channels of losses (Kapp, 1933).

e. Soils with an Abnormal Content of Salt. Although the continental "alkali soils" have been studied extensively in different countries—however mostly without particular attention to their nitrogen metabolism—the nitrogen regime of marine soils, containing the salts of sea water, has been only sparsely investigated. In 1948 Chaloust published a paper on the ammonification in the soils of the Camargue, where all gradations in salt content can be found. He reported that moderate salt concentration proved to be rather harmless to the ammonification of added blood meal. The nitrification of ammonia proved to be more sensitive to sodium chloride, as was shown by Yankovitch and Yankovitch (1953), but yet the salt tolerance of the nitrifying bacteria is higher than that of most crop plants.

From 1928 onwards an extensive study has been performed on the reclamation of the soils of the enclosed areas of the Zuiderzee. The nitrogen mineralization was also studied, beginning before the enclosure, in the bottom of the sea, and continuing until the soil attained the normal conditions of cultivated land. Most of these investigations remain unpublished as mimeographed internal reports, but the main results are summarized in some reviews (Harmsen, 1932, 1955a). The most important results of this work are that, though the microflora of the original sea bottom proved to be rather sparse and consequently all metabolic processes there to be slow, after enclosure and draining of the soils the ammonification increased rapidly. As a consequence

this new land during the first one or two years mineralized much nitrogen and produced a luxurious growth of weeds and volunteer plants. But after one or two years the initial fast accumulation of mineral nitrogen reverted into a very slow process, with a pronounced response of the crops to nitrogen fertilization. It is not clearly understood whether this short period of abundant liberation of nitrogen was due to a certain fraction of the organic substance in the sea bottom, readily mineralizable and with a narrow C:N ratio, that became exhausted within the first two years; or was the result of an entire lack of fresh plant residues with a wide C:N ratio until the first vegetation of plants provided for such material. During the subsequent years the soils of the Zuiderzee marshes never again produced mineral N as abundantly as just after drainage.

Another series of investigations of soils impregnated with sea water was performed during and after World War II in the areas flooded as a result of warfare. Here, however, it was not virgin sea bottom to be reclaimed but old cultivated land to be recovered. This subject will be discussed in Section II, 8.

f. Arid versus Humid Conditions. The opinion, advocated by some authors around the years 1910 to 1915, that the often observed relatively high concentration of NO_3-N in arid soils was due to a higher rate of mineralization in such soils than in humid soils (Hilgard, 1906; Headden, 1910, 1911), has definitely been disproved by Stewart (1913a, b), Stewart and Peterson (1915, 1916), and Lipman *et al.* (1916). These workers demonstrated a more vigorous mineralization under humid, than under arid conditions, ascribing the incidentally high concentration in the latter to lack of leaching and to capillary rise from the subsoil, though the decomposition of nitrogenous organic matter in arid regions proves to be high enough to cause a depletion of the nitrogen reserve of most of those soils. In the older literature this gradual depletion was denied by some authors, as is reviewed by Gainey *et al.* (1929). Soon, however, increasing evidence for the opposite opinion accumulated, and numerous investigations demonstrated clearly that under the conditions of arable land the organic matter in arid and subarid climates decreases as well as in humid climate, though at a lower rate (Gainey *et al.*, 1929; Swanson and Latshaw, 1919; Sievers and Holtz, 1922, 1923, 1924; Prescott, 1934; Cornish, 1949; Miller and Krusekopf, 1932; Jenny, 1930, 1933, 1941; Brown *et al.*, 1942; Caldwell *et al.*, 1939; R. Newton *et al.*, 1939; J. D. Newton *et al.*, 1939, 1945; Kardos, 1948; Ching-Kwei-Lee and Bray, 1949, and Salter and Green, 1933, being only the most prominent papers). Consequently at present not a fundamental but only a quantitative differ-

ence is accepted in the nitrogen metabolism of arid and humid soils, and this difference is even more reduced by application of the various measures adopted in dry-farming systems to conserve moisture in the soil. Since mineralization of nitrogen can only proceed when there is enough moisture in the soil, all these measures will prolong the period of possible mineralization and thereby stimulate the crops, but also accelerate the decomposition of the organic matter in the soil. Prescott (1934) in his excellent review of the situation in the Australian wheat belt gave a clear outline of this situation, and in recent years Atanasiu (1947) again underlined this effect of the dry-farming system for the conditions of Rumania, thus confirming the old investigations of Dojarenko.

However, the recent publication of Doughty *et al.* (1954a) elucidated an interesting characteristic of soils in semiarid regions. The natural grass cover uses so much moisture that the precipitation never penetrates beyond the level of root development. Under prairie conditions consequently no leaching of nitrate takes place. But after breaking the virgin soil leaching of nitrates could be observed, especially during fallow years. The opinion of Caldwell *et al.* (1939), who presumed leaching to be negligible under those conditions, is disproved.

The decomposition of humus in arid climate is even more accelerated by irrigation, but thereby entirely new conditions are created, which have already been mentioned in Section II, 3*b*.

4. *Nitrogen Balance in Soil*

Although the whole complex of questions about the seasonal mineralization and immobilization of nitrogen were posed at the very beginning of this century, and the fundamental problems involved may be regarded as solved, some aspects still are investigated and discussed, even in quite recent papers.

The rule that in temperate climate mineralization is optimal in spring and gradually decreases during the summer season, regardless of cropping and other measures, has long ago been recognized, and correctly interpreted as the "partial sterilization effect" of freezing of the soil in winter. In recent years Landrau (1953) again underlined this observation.

As far back as in 1901 King and Whitson already were struck by the observation that the absorption of mineral nitrogen in cropped land had its optimum not at the time of maximal growth of the crop but during the latest stages of its development, just before ripening. This observation was confirmed by many earlier investigators (King and Whitson, 1902; Jensen, 1910; Russell, 1914; Whiting and Schoonover,

1920; Lyon and Bizzell, 1911, 1913a, b, 1918; Gowda, 1924; Starkey, 1929a; and others). Some recent papers again mentioned this peculiar course of N uptake by annual crops (Goring and Clark, 1949; Clark, 1949). No correct interpretation was given until Bizzell (1922) arrived at the conclusion that the loss of mineral N in cropped land can be attributed only partly to the uptake of N by the plant roots, and that much mineral N is fixed by microbes thriving on carbonaceous root excretions and plant residues formed by the growing crop. This conclusion resulted from field experiments and from a study of root excretions of plants grown in liquid media (Lyon and Wilson, 1921). It was rapidly generally accepted and backed by other investigators (Lyon *et al.*, 1923, 1930; Lyon and Bizzell, 1936; Starkey, 1931b; and others); and even in some recent papers this conclusion is again underlined (Goring and Clark, 1949; Richardson, 1938; Pinck *et al.*, 1948a, b; Gerretsen, 1949; Gaspart, 1949). The old tricky problem of the loss of nitrogen in most nitrogen balances, as presented by Russell (1914), Lyon and Bizzell (1918, 1936), Bizzell (1922), Lyon *et al.* (1923), Starkey (1931b), Pinck *et al.* (1948a, b), Gaspart (1949), who all found that in cropped soil the sum of total nitrogen in the crop plus the mineral nitrogen in the soil at harvest time generally was smaller than the mineral nitrogen in the soil at the beginning of the growing season, could now better be understood.

However, not all investigators had the same experience. King and Whitson had already observed in 1902 a case of the reverse situation, when there was a surplus of nitrogen in the crop + mineral nitrogen in the soil at harvest time above the amount of mineral N in fallow land at the same time, and later more such cases were reported. Lyon *et al.* (1923), Bizzell (1922), and Starkey (1931b) studied this controversy in more detail, as a result of which it was understood that it depends on the conditions whether "losses" or "gains" of nitrogen will result. Generally it can be said that high levels of mineral N, insignificant leaching, and a rich development of the crop will bring about considerable immobilization of N by the rhizosphere organisms, and consequently will result in an apparent "loss" of mineral nitrogen. These losses therefore are most apparent when high amounts of nitrogenous fertilizers are applied, especially when ammonia fertilizers are used (Bartholomew and Hiltbolt, 1952; Norman and Krampitz, 1945). Since then Jansson *et al.* (1955) has demonstrated a preferential utilization of ammonia by microbes. Therefore the general rule has gradually been derived that with high applications of nitrogenous fertilizers significant immobilization of nitrogen by carbonaceous material in soil may be expected, and consequently only a partial recovery

of the applied N in the crop, while with low fertilization the N in the crop may even be higher than the application (Richardson, 1938; Bizzell, 1944; Gaspart, 1949). Pinck *et al.* (1948a, b), applying heavy fertilization with urea, never got more than 50 per cent of the applied N back in the crops, and in pots receiving a nonleguminous green manure, still less of the N was recovered in the crop.

Of course these so called "losses" of nitrogen, being the incorporation by microbes of mineral forms of N into the big stock of organically bound nitrogen, are only a temporary feature. How stable this binding is depends on the type of the carbonaceous material and on many other conditions, but in most cases the fixed nitrogen readily reappeared again in mineralized form as soon as the addition of fresh organic substances with a high C:N ratio stopped with the harvest of the crop, or as soon as soil samples were collected from such plots and incubated. Recently, observations of such sharp differences between the soil outdoors and after sampling have been reported by Clark (1949), Barnes (1950), and Baumann and Schendel (1952). They all observed more N mineralization subsequently if the soils were cropped than if fallowed; this can be considered as logical and consequent. Clark even claims a general rule that the increase in mineralization after cropping of a soil is about equivalent to the decrease in mineralization during the growth of the crop, a rule presumably valid only for normal conditions. A very careful study of this whole complex of problems has been performed by Bartholomew and Clark (1950a, b).

Whereas in arable land with annual crops under ordinary conditions the mineral nitrogen immobilized during the growth of the crop becomes again liberated during the subsequent fallow period, this liberation remains incomplete or is even entirely suppressed under perennial crops or when high amounts of organic substances with a high C:N ratio have been added to the soil. The immobilization of mineral nitrogen in such cases has a more or less permanent character, because a great deal of the nitrogen now becomes bound not only as the protoplasm of the active microflora but also as stable humus, which might close the gap between the nitrogen added to the soil in any form and that removed in the crop, not accounted for by the negligible leaching and volatilization. Of course, this explanation presumes a gradual, though slow, increase of the total organic matter in and on the soil.

It is evident that in all soils with more fixation than mineralization of N throughout the whole year cycle, there must be a gradual increase in total N in the soil—a conclusion already arrived at by Lyon and

Bizzell in 1918. Generally an increase in total N in a soil brings about an increase in the total organic matter, since in most cases nitrogen and not carbon in the added residues is the limiting factor for accumulation of humus; therefore conditions sparing for total nitrogen are favorable for the build-up of humus, as occurs in grassland and under other permanent plant cover.

Innumerable are the papers dealing with the accumulation or depletion of humus in soil and the consequences of it, but since they are mostly beyond the scope of this review, only a few of the more important will be briefly mentioned. Spectacular reports of an accumulation of total nitrogen and humus in young grassland or in leys on previously arable land are given by Bizzell (1944) and by J. D. Newton *et al.* (1939) in recent years, and in many earlier papers. Penman (1949) was unable to demonstrate an appreciable increase in total N within three years of a subterranean clover ley and arrived at the conclusion that about ten years of a clover ley are required for a measurable increase in total N in the soil. It is still too often forgotten that total N in soil is 20 to 1000 times as high as mineral N. This paper of Penman (1949) and contemporary reports of Sims and Jardine (1949) and of Bath (1949) as well as the publication of Clarke and Marshall (1947) present many valuable data about maintenance of organic matter and N_t in Australian soils. They also contain figures showing increase in nitrogen mineralization by incorporation of clover leys in the rotation system.

A very fast accumulation of total N and humus has been reported by Theron and Haylett (1953) on grass leys in South Africa in a semiarid climate, but only with addition of nitrogenous fertilizers. Although arable crops in those soils required only light dressings with N, the grass ley showed in the second and subsequent years all characteristics of N starvation, thereby demonstrating spectacularly the active immobilization of all mineral N by the accumulating plant residues in grass leys. Apparently available N was the limiting factor for the growth of the grass, and also for humus synthesis in this ley on an acid soil (pH 4.2 to 5.4) and with no legumes. Without application of N fertilizers this poor state was maintained for many years, with only very slow accumulation of humus and total N and with permanently low yields. But as soon as heavy fertilization with N was applied, the grass growth was immediately stimulated, and the synthesis of humus also was accelerated. Within eight years the total carbon and total nitrogen were raised to 1.75 and 0.113 per cent, respectively, above 1.61 and 0.105 per cent initially. By these results Theron and Haylett

were led to advise heavy fertilization with N on all grass leys containing no legumes, since N was recognized the limiting factor in that crop, much more so than on old permanent grassland.

In 1950 't Hart published a short but very clear and stimulating review of the problem of the accumulation of organic substances in grassland and the fast depletion thereof in arable land. Many statistical data for the conditions of Holland are summarized therein, and schematical presentation is given of the course of synthesis of humus in new grass leys.

Of course, even under the most favorable conditions the accumulation of total nitrogen and humus cannot go on indefinitely, and gradually equilibria are reached whereby the same amount of nitrogen becomes fixed as mineralized. This situation is characteristic for all stabilized old plant associations (virgin forests, permanent grassland, prairies, savannas, etc.). In the paper of Richardson (1938) such permanent grasslands with a constant humus and total-N content have been compared with younger grasslands and with grass leys. A regular relation has been found, represented by a curve, gradually approaching the horizontal. Under the given conditions near Rothamsted, arable land had an N_t content of *ca.* 0.15 per cent, whereas the stabilized level of permanent grassland soil was *ca.* 0.28 per cent, but this level was reached only after about 200 years.

't Hart (1950) also mentioned the trend towards the final state of equilibrium in old grassland. Further he underlined the fast accumulation of humus in grassland soils and emphasized the use of leys in the rotations on arable land. Many other investigators also arrived at the same conclusion, and it became widely accepted that a satisfactory humus level in arable land can be maintained only when grass or clover leys are introduced in the crop rotation.

Accumulation of total N and humus with N dressings, common on grassland and leys, has in some cases been observed even on arable land (Bizzell, 1944; Pinck *et al.*, 1948a, b). In these cases, of course, formation or addition of much carbonaceous matter is necessary. The accumulation of humus reported by Pinck *et al.* (1948a, b) in their pot experiments is surprisingly high; within three years of cultivation of Sudan grass or wheat in pots, without any organic manuring and with only heavy dressing with urea, they obtained an increase of organic matter of 24 per cent of the original. It seems scarcely possible to ascribe this rapid increase entirely to the synthesis of genuine stable humus, and retarded decomposition of plant residues with the accumulation of only partly decomposed matter with a high C:N ratio may be presumed in this experiment.

To summarize the above data about humus and N_t maintenance the generally accepted rule can be formulated: in permanent grassland, and in most virgin plant associations both tend to accumulate, but they become rapidly depleted as soon as the virgin land is tilled and reclaimed. Lawes (1889) already gave a clear statement of this rule. The full realization of the consequences of this rule only gradually conquered the minds of all people responsible for agricultural production. Unjustifiable methods of farming have been, and are still, applied everywhere, reducing the level of humus and N_t to the low equilibrium level characteristic of old arable land. In most old countries (Europe, New England States) this final equilibrium (with only some 0.05 to 0.1 per cent of N_t) is already reached, but even the vast prairie regions in Eurasia, the Americas, Australia, and Africa are approaching this situation. It is therefore understandable why the most alarming reports about a fast depletion of humus and total nitrogen are presented by workers in such countries (Theron, 1951; Theron and Haylett, 1953; Penman, 1949; Cornish, 1949; Prescott, 1934; Miller and Krusekopf, 1932; Jenny, 1930, 1933, 1941; Brown *et al.*, 1942; Caldwell *et al.*, 1939; R. Newton *et al.*, 1939; J. D. Newton *et al.*, 1939, 1945; Kardos, 1948; Salter and Green, 1933; Ching-Kwei-Lee and Bray, 1949; Mohr, 1930; Gustafson, 1945, 1948; Doughty *et al.*, 1954a; Doughty, 1948; Lehane and Staple, 1943), the more so since in some of these young countries with big farms and a dry climate often still no fertilizers or at least no nitrogen fertilizers are applied, and still some undesirable or unfavorable crop rotations are practised, with only cereals sometimes raised year after year, or with cereal cultivation interrupted only by fallow seasons.

On plots which already have attained the humus and N_t levels of old arable land, of course, no further decreases are observed. Iversen (1953a) even claimed that practically all experiments in Denmark failed to show any depletion in humus, N_t, or fertility of the soils managed without application of organic manure. This result, however, must be considered in the light of the fact that in Denmark on much of the arable land grass-clover leys are incorporated in the rotation.

Barbier *et al.* (1950) and Lefèvre and Drouineau (1951) drew attention to the ability of the residual humus in the soil to liberate considerable amounts of nitrogen even after many years of mistreatment and exhaustion of C_t and N_t. A confirmation of this observation was obtained by Harmsen in 1938 (unpublished report), who observed that when old arable soil is plowed to a depth of 20 cm., turning this layer nearly upside down, the activity of the microflora in the former upper 5 cm., now turned down to the depth of 15 to 20 cm., only gradually

decreased while in the formerly deepest part of the turned soil, now the upper 5 cm., then was developed in some days a microflora even more active than that of the upper 5 cm. before plowing. A consequence of this development of a microbial population after plowing was an enhanced microbial activity and mineralization of organic matter. This phenomenon is perhaps repeated on arable land every year. It demonstrates clearly the important influence of any type of regularly repeated tilling of the soil. A similar observation was reported by Mischustin and Schukowskaja (1949). Interesting data about the differences in the process of mineralization of organic compounds in arable land and in virgin prairie or forest soil have been given by Rendig (1951). He performed a fractionation of the organic nitrogen in these soils and found in the arable plot a lower N_t and also a lower percentage of nonbasic amino- and amide-nitrogen in the N_t and a higher percentage of humin-nitrogen than in the two virgin soils. Here again a faster decomposition of plant residues in arable land is demonstrated.

At the Soil Microbiology Conference (Purdue University) in 1954 Allison reviewed the basis of calculation of the nitrogen balance in soils. It is disappointing that Allison had to arrive at the conclusion that " . . . From the facts presented, it is obvious that regardless of years of research, we seldom can draw up a soil nitrogen balance sheet for a field soil that is accurate. . . . " So we must accept the fact that a nitrogen balance can be accurate only for soils kept in containers under strictly controlled environmental conditions, and never under field conditions.

5. *Influence of N_t on Mineralization of Nitrogen*

Another old problem is the relation between total and mineral nitrogen or between total nitrogen and the rate of mineralization. Many old papers discussed this question and sometimes arrived at entirely contradictory conclusions. However, most investigators in those days especially Fraps with collaborators, (Fraps, 1912, 1920, 1921; Fraps and Sterges, 1932, 1939a, 1947), found that the higher the total nitrogen in the soil, the more mineral nitrogen is provided for in incubation experiments and under field conditions. More or less unintentionally all their studies were performed with soils of a uniform type, with differences originating only from variation in treatment, manuring, and crop rotations. In their later work Fraps and Sterges (1939a, 1947) investigated also widely different soil types and realized that the same total nitrogen content in fundamentally different soils can bring about entirely different mineralization powers; nevertheless, they maintained their opinion that the mineralization of N depends primarily on the

amount of total N in the soil, if only some individual impediments are first removed by bringing them to a uniform structure, moisture content, pH, and mineral supply by grinding, seiving, liming, fertilizing, and inoculating the samples, and by maintaining strictly standardized temperature, aeration, and moisture content in the soil samples. This conclusion was attained even with fundamentally different soil types, but still in those soils the differences in N_t were the result of differences in the conditions, more or less favorable for the accumulation of humus and N_t. Carpenter *et al.* (1952) arrived at the same conclusion. They also found very close correlation (significant to the 1 per cent level) between the yield of wheat and the N_t content of the upper 12-inch layer of soil in a cumulative rotation experiment.

Gainey with collaborators, however, who long ago started the study of N mineralization (Gainey, 1919a, b, 1920; Gainey *et al.*, 1929; Gainey and Sewell, 1932) arrived in their recent papers (Gainey, 1936; Gainey *et al.*, 1937) at just the reverse conclusion, because they used for their work samples derived from the same soil type but from spots known to be very different in their power to form mineral nitrogen. The most spectacular example of such variations was found in the so-called "spotted" field crops, showing green spots amidst the rest of the field which carried a nitrogen-deficient crop. Such N-rich spots had practically the same N_t but more than twice the NO_3 production of the rest of the plot. By these and other similar results Gainey finally formulated his opinion that the N mineralization and fertility of a soil are more intimately associated with the characteristic properties of a small part of the total N, than with all of it. A small part is active; the rest is very stable and therefore rather inert. This view agrees with that of Crowther and Mirchandani (1931). In both these cases, however, the mineralization power depends not on more or less accumulation of normal humus but on special sources of mineral nitrogen. Even capillary transportation of mineral N or the temporary formation of residues extraordinarily rich in nitrogen may be responsible for the different rates of mineralization, especially when the soil samples are incubated at optimal conditions. The modern and very careful investigations of Allison and Sterling (1949) once more checked this whole problem. Using plots in a long-term fertilization and crop-rotation experiment on one, originally very uniform, soil, they could fully support the opinion of Fraps and Carpenter *et al.*, on the close relation of N mineralization with the N_t content (correlation coefficient of 0.7 to 0.8); nevertheless they understood that this conclusion holds true only for one soil type. This indicates one of the limitations of the applicability and reliability of incubation tests, as will be discussed in Section IV. Of course, the

correlation between N_t and mineralization cannot be expected to be complete, since Allison and Sterling (1949) themselves found an even closer, though negative, correlation between mineralization and the decrease in N_t during the preceding years—a logical consequence of selective decomposition of the least stable fractions of the humus.

6. *Mineralization of Nitrogen from Added Organic Substances*

Since the fundamental problems about the mineralization of nitrogen have been reviewed, particularly with reference to the native humus in the soil, in Section II, 1–5, the following discussion of the mineralization of organic additives will be dealt with concisely.

a. Effect of C:N Ratio on Mineralization. The importance of the C:N ratio of the organic substances in soil has already been mentioned. It has long been recognized that not only the native organic matter of the soil, but also any organic substance, applied as manure to the soil, must be evaluated with regard to its C:N ratio. Numerous earlier papers were devoted to the study of this problem (Kelley, 1915; Sievers and Holtz, 1922, 1926; Fraps, 1922; Rege, 1927; Waksman, 1924; Waksman and Tenney, 1927, 1928; Tenney and Waksman, 1929; Waksman and Diehm, 1931; Norman, 1929, 1933; Jensen, 1929; Lemmermann *et al.*, 1930; Crowther and Mirchandani, 1931; Mirchandani, 1931; Niklewski, 1935; Cunningham, 1927; Daji, 1934; Raju, 1936), to mention only the most important. Fairly close agreement was obtained by all these investigators as to the limits of N content of the added material, below which no mineralization of N may be expected. This is 1.5 to 2.0 per cent of the dry matter, corresponding to a C:N ratio of 20 to 25. These figures are generally accepted as correct up to the present time. Millar *et al.* (1936) confirmed the leading role of the C:N ratio upon the rate of NO_3 accumulation, and recently Barnes (1953) published a paper with the same conclusion. As Barnes used a light soil, very poor in total nitrogen, the mineralization rate was surprisingly low in the unmanured soil, and even moderate application of $(NH_4)_2SO_4$ entirely suppressed the mineralization of N from humus. But the nitrogen of added ground mustard or vetches became entirely mineralized within some 10 weeks. Only the grain straw with its very low N content suppressed the mineralization of nitrogen for the full 89 weeks of incubation. Parbery and Swaby (1942) checked this problem under the climatic conditions of New South Wales. They found an N content of the organic additives of 2.5 per cent as minimum for guaranteeing unhampered N nutrition of the crop, whereas from materials with less than 1.5 per cent N no N whatever was mineralized during the first months. See also Norman

(1947). Bould (1948) made an extensive study of the mineralization of nitrogen in compost before and after application to the soil. He again confirmed the above-mentioned figures, as did Pinck *et al.* (1948a, b) in the same year. Owen *et al.* (1950a) carefully investigated the mineralization of N from organic compounds with known and constant composition and structure, using amino acids for this purpose. They observed a close inverse correlation between the rates of N mineralization and the C:N ratios of the acids when added to soil. By this work of Owen and associates doubts about the influence of the C:N ratio of amino acids on the mineralization of their N, expressed by Batham in his first paper in 1925, but partly withdrawn in his later publication in 1927, were removed. Lees (1948b) and Quastel and Scholefield (1949) arrived at the same conclusion using their percolation technique.

Apparently these values in most cases are correct, but Rubins and Bear (1942) criticized the general attitude towards the relation of the C:N ratio and the ease of mineralization of N in organic substances by pointing out the significant differences in resistance to microbial attack of the different fractions of the carbon and nitrogen compounds in the substances studied, as has already been expressed by Waksman and Tenney in 1927. The very resistant lignin, for instance, scarcely inhibited the mineralization of N, whereas sugars or cellulose were most effective. Similarly the nitrogenous compounds in bone meal and in process tankage are highly resistant and therefore not readily mineralized even when the C:N ratio is low. Smith (1940) and Peevy and Norman (1948) arrived at similar conclusions, especially underlining the high degree of resistance of lignin.

One of the most important consequences of the role of the C:N ratio in the decomposition of organic substances in soil is the adverse effect of application of straw in soil on the N nutrition of plants. This subject with its extensive literature is too much a special problem to be discussed here; besides, it was practically entirely solved before 1935 (see Richards and Norman, 1931). But it should not be forgotten that it still is an important practical problem with two aspects: one is the need to get rid of the superfluous straw and chaff especially in those areas where it has no commercial value; the other is the desire to use this available material to spare the mineralized nitrogen and to protect it against leaching out. Only some outstanding recent papers on straw application will be mentioned here. Throckmorton (1943) reported some experiments with straw application performed in a light rainfall area in the United States. The sparing effect of straw on the total nitrogen clearly was demonstrated in these experiments, whereas only an insignificant effect on the conservation of total organic content of the

soils was achieved. The adverse effect on the first crop after application —i.e., the nitrogen deficiency—was not as significant under these semi-arid conditions with relatively low yields of straw often applied just before a fallow, as in areas with a humid climate, where appreciable amounts of straw never can be applied without prior composting or simultaneous addition of nitrogen.

An extensive study on the immobilization of mineral nitrogen by application of straw was published in 1954 by Van Maercke, who especially tried to determine the minimum amount of N fertilization to overcome the adverse effect of straw. Bjälfve (1952, 1953) in a recent series of papers also tried to find the most economic way to apply straw without injurious immobilization of the nitrogen. Under Swedish conditions he arrived at the recommendation to apply the straw either on plots before cultivation of legumes or on leguminous crops at the time of plowing under. All these investigators demonstrated the proper principles to be followed, but it should not be forgotten that no uniform advice can be given, because local conditions are often so very different.

Interesting problems also arise when soil is covered by a mulch. The mineralization of nitrogen and the accumulation of nitrates can be influenced hereby in more than one way:

1. The mulch, generally being a material with a wide C:N ratio, can partly interfere with the mineralization in the soil by absorbing the available nitrogen. This action will be stimulated by partial mixing of the mulch with the upper part of the soil or by any means bringing about close contact of mulch and soil. But even a material loosely spread upon the soil can be decomposed when kept wet during cool weather with much precipitation. Its soluble decomposition products may be transported by the rain to the soil and act there as N absorbents. This effect of a mulch was presumably experienced by Mooers *et al.* (1948), since they got in their lysimeter experiments much higher recovery of applied nitrates or ammonia on bare land than under straw mulches. Perhaps in some of the experiments of the extensive study of mulch farming by McCalla and Russel (1943, 1948) this N-absorbing effect of straw mulch has also played a role. Some older papers, for instance, those of Albrecht (1922) and Albrecht and Uhland (1925), also mention experimental results strongly indicating N fixation by the mulch material.

However, the use of material rich in nitrogen for mulching orchards in Massachusetts was found by Beaumont *et al.* (1927), Beaumont and Chapman (1933), and by Moore and Beaumont (1934) to increase nitrate production in plots annually mulched, the more so since the mulch material in their case became nearly entirely decayed within one year.

2. A mulch layer protects the soil against drying out, against compacting by heavy rain, and against too high temperature on sunny days. By these actions the topsoil is kept constantly in moist condition, cool, and in an ideal loose crumbly structure. Mineralization and nitrification can be stimulated thereby. Such favorable effects of mulching have been reported by Chase (1948) and by Stevenson and Chase (1953). They compared the nitrifying capacity of mulched and unmulched soils, using the technique of Lees and percolating them with a solution of $(NH_4)_2SO_4$. The mulched soil proved to have a much higher rate of nitrification and did not show any lag period. Stevenson and Chase therefore consider that the mulch kept the nitrifying organisms at near optimal development. However, the mulch used in these experiments consisted partly of alfalfa, thereby providing much organic nitrogen to the soil. McCalla and Russel (1943, 1948) also in some cases obtained examples of a favorable effect of mulches on mineralization of nitrogen, but often the effect was decidedly adverse either because mineral N was absorbed by the mulch material or because the temperature was so much lowered that mineralization became reduced as compared with bare soil.

3. Especially under more or less arid conditions a mulch, by keeping the soil surface loose and reducing the evaporation, can prevent the capillary rise of nitrates to the surface and the accumulation of nitrates in the top soil during a dry season. The rains of the next wet season then penetrate easily into the soil instead of partly running off, and the soluble N is washed out more completely than from unmulched crusted soil. This effect has been observed by McCalla and Russel (1943, 1948) and also very spectacularly by Griffith and Manning (1950) in Uganda soils. The contradictory results often obtained in mulching experiments justify the general conclusion that no constant rule can be formulated; too many divergent conditions may influence the effect of the mulch.

The role of the C:N ratio in the organic substance, as it has been discussed in this section, whereby material of high nitrogen content stimulates bacterial activity and consequently facilitates the decomposition of the organic substance and the liberation of CO_2, sometimes can be reversed by the role of nitrogen in humus synthesis. In such cases a greater part of the original organic matter sometimes becomes transformed to stable humus compounds, resulting in a sparing effect of high nitrogen content on the carbon. Such cases have been reported by Millar *et al.* (1936) and by Turk and Millar (1936). Peevy and Norman (1948), however, could not demonstrate any appreciable effect of nitrogen on the maintenance of carbon. Here again, presumably no rule valid for all cases can be given.

b. Farm Manure and Compost. In the literature on the mineralization of organic N in farm manure and compost the effect of the C:N ratio again occupies a dominant position. This subject has been extensively studied for many years, and the publications are innumerable. It was practically unanimously recognized in the older papers that the organic N of farm manure and of any type of compost only slowly becomes available to the crop, and as a result of the activity of several careful German investigators (Schulze, 1911; Schneidewind, 1910, 1928; König, 1929; Scheibe, 1929; and others) it was agreed that during the first year generally no more than 25 per cent of the total N of the farm manure could be used by the crop, despite the fact that part of the N in manure is present as free ammonia. It was also already fully understood that the rate of mineralization of manure N depends on its type and composition; however, some mineralization could always be observed, even in the first year after application.

It was therefore a surprising announcement, made by Barthel and Bengtsson in a series of papers covering a long range of years from 1917 to 1940, that in their experiments the organically bound form of N in farm manure was *not* mineralized at all for two or more years (Barthel, 1918; Barthel and Bengtsson, 1918, 1920, 1924, 1926, 1930, 1931a, b, 1934, 1939; Bengtsson, 1924, 1932, 1936; Bengtsson and Barthel, 1935, 1940). They performed many incubation tests adding farm manure to different soils in various amounts. In the earlier papers of this series no grounds could be found to explain this experimental result, so entirely different from the common opinion; but their later papers, especially the two last-mentioned recent publications, gave more details, explaining the peculiar results of their experiments. In most cases the manure used by them had a high amount of straw and a wide C:N ratio, whereas in some other experiments very old manure was used containing much resistant humus-like material. Moreover, they found very significant differences in the rate of mineralization between manure produced by cows fed hay, straw, and concentrates and another batch from animals fed on pasture. In the first-mentioned type the mineralization of N proved to be extremely slow, whereas the other type showed mineralization percentages of the usual magnitude. This demonstrates how dangerous it is to generalize results obtained with one type of manure or one set of conditions. Virtanen (1935) reported a similar experience comparing farm manure obtained from cows on silage or pasture with manure from animals fed hay, straw, and crushed oats.

Jensen (1931, 1932, 1952) performed experiments similar to those of Barthel and Bengtsson. The manure types used by him proved not

to be so extremely resistant as those of Barthel and Bengtsson, but his final conclusion is that the mineralization of the organic N in farm manure is generally too slow to provide appreciable N nutrition for crops with a short growing season, such as cereals. Only crops growing during the entire summer until the autumn and crops in subsequent years can utilize part of this N. Poulsen (1950) and Iversen and Dorph Petersen (1951) and Iversen (1953b) recently confirmed the results of Jensen's laboratory experiments in pot and field trials. Slightly more favorable figures of liberation of about 40 per cent of the total N in farm manure within 150 days were reported by Lindhard (1944). The investigations of Jensen carefully traced the course of decomposition of manure in pot experiments. Usually with all types of manure a rapid decrease of all available N in the soil-manure mixture was shown during the first weeks, when the readily mineralizable carbonaceous substances were attacked, coinciding with the maximum development of microbes. Some weeks or months later, during the decomposition of the first generation of microbes, mineralization of organic N of the manure became apparent and in some of the experiments of Jensen, reached more than 30 per cent of the total organic N within some nine or ten months. Yet Jensen arrived at the conclusion that the rate of mineralization of the N of manure did not correlate with the C:N ratio or that this relation was obscure. The liberation of N depended too on the absolute nitrogen content of the substance, and on the resistance of the nitrogenous and of the carbonaceous compounds of the manure (Poulsen, 1950). This is a confirmation of the opinion of Rubins and Bear (1942). In 1952 Jensen studied the mineralization of farm composts in laboratory experiments, incubating these composts mixed with sand. Twenty to thirty-three per cent of the total N became mineralized within nine months at about 25° C. At temperatures between 5 and 10° C. the mineralization nearly entirely stopped in spite of higher numbers of microbes at this temperature than at 20° to 30° C.

All the above-mentioned investigations, and numerous field trials, as well as the experience of farmers, agree on the point that the organic N of farm manure, and of compost, only slowly becomes available and seems never to be completely utilized by crops. Under field conditions a considerable part of the nitrogen can be leached out from the soil, but laboratory experiments in which any loss through leaching was impossible, definitely showed that the mineralization gradually became slower and seemed to come to a standstill, sometimes with more than half of the organic N still unmineralized. Lindhard (1944) observed clear examples of this in field trials. A logical consequence of this ob-

servation would be a gradual accumulation of stable humus fractions in soils regularly manured. Such an accumulation, however, has never been observed under field conditions. It is again Jensen (1952) who presumably gave the correct explanation of this phenomenon when he drew attention to the fact that, although in most laboratory experiments, where no leaching occurs, the mineralization of the resistant part of the manure indeed stops, a slow but continuous mineralization can be observed, when the accumulated nitrates are removed by percolation. Under field conditions this slow decomposition of even the most resistant fractions of the added manure and of the native humus apparently proceeds faster than its accumulation from the manure applied.

Though it is not directly pertinent to the subject of this review, it seems worth while to mention here the controversy between the old opinion emphasizing the addition of as much straw as possible to the manure with the intention of increasing the amount of organic matter added to the soil, and the opposite standpoint, denying the value of the additional straw. The former procedure has recently again been proposed by Zutavern (1950, 1952). Opposing this opinion, Iversen (1931), Bucher (1943), and recently Sauerlandt and Berwecke (1952) and Köhnlein and Vetter (1953b) correctly showed (1) that a high content of straw is responsible for too high C:N ratios, and (2) that the loose structure of such manure piles brings about very high temperatures and a rapid decomposition of the carbonaceous substances, with finally an even lower total output of manure than when made with less straw.

The decomposition in soil of different types of composts (urban and farm composts and artificial products prepared from different types of peat with admixture of organic wastes or mineral constituents) and the liberation of nitrogen from these products have recently been elaborately studied. This field of research is developing along its own, highly practical, empirical lines, and therefore has had to be excluded from this review. For more information the reader must be referred to some review articles on this subject: Kortleven (1951); Springer and Steigerwald (1951); Ayyar (1933); Univ. California, Tech. Bull. No. 1 (1950), No. 9 (1953); Wylie (1952); Bould (1945); Hulsbos (1953). A critical study of all experiments with urban compost performed in the Netherlands from 1880 to 1946 has been published by Kortleven (1950).

In the preceding pages only papers dealing with the decomposition of manure and compost after addition to soil has been mentioned. The changes occurring in the heaps during composting have been inten-

tionally omitted as being a special subject outside the scope of this review. One question connected with the process of composting, however, must be mentioned here, that is, the controversial opinion about the desirability of composting the wastes before application to the soil. All investigators agree of course on the necessity of applying as organic additives only substances with a sufficiently narrow C:N ratio as not to cause N deficiency in crops, but some workers consider that it is the process of active mineralization, and not just the presence of organic matter in the soil, which is needed for improvement of its structure and for activation of the microflora. Therefore they emphasize the desirability of applying as much organic waste material as possible, if need be entirely undecomposed, and of neutralizing the harmful effect on N nutrition by addition of nitrogen fertilizer. Experiments in support of this opinion have been reported by Crowther in 1943 and by Bould in 1948, but it is still doubtful whether this procedure would be profitable financially, and moreover the spreading of manure or compost in the field is facilitated by prior decomposition.

Interesting data are presented by Kaila (1954), who demonstrated a significant lowering of the pH values during composting or decomposition in soil of organic material (straw) without liming, but with addition of much nitrogen in the form of ammonia or urea, due to the formation of nitric acid. Similar observations were mentioned earlier by Hesse and Schmalfuss (1938) and by Schulze (1939), in preparing straw composts. Organic matter comparatively rich in nitrogen, and subject to rapid decomposition, even without addition of nitrogen, can become more acid when, during composting, much nitric acid is formed, as has been shown by Gordon (1936) and again by Kaila (1954). This acidification, induced by too high nitrogen content, sometimes is even responsible for a retardation of the entire process of decomposition. So it can be accepted as proved that an optimal rate of decomposition of raw plant material can be achieved by the proper dosage of mineral nitrogen and not by application of as much N as possible.

The use of liquid manure has not been considered here since most of the N in it is ammonia N or some readily mineralizable soluble amino compounds.

c. Other Additives. Since time immemorial many different organic wastes have been used for manuring soil, and the number of older papers dealing with nitrogen liberation from them is rather high. During the period covered by this review, however, a few papers appeared presenting some new aspects. A remarkable series of careful studies has been published in recent years by Owen *et al.* (1950b, 1951) and by Owen and Winsor (1950a). They mixed different organic wastes, all

with a very narrow C:N ratio with soils in pot experiments without cropping and without preventing leaching of soluble products. Blood meal, horn and hoof meal, meat meal, fish meal, Peru guano, bone meal, glycine, urea, and $(NH_4)_2SO_4$ were compared. The mineralization of N in glycine and in guano proved to be very fast, equaling the nitrification of $(NH_4)_2SO_4$. Additions representing as much as 300 p.p.m. N became nitrified within some 6 days of incubation. The materials containing the N mainly as proteins (blood meal and horn and hoof meal) had a much slower mineralization, reaching after 65 days of incubation only 68 per cent of the total N in blood meal and only 58 per cent in the horn meal. However, not only was the mineralization of the proteinaceous products slower, but it tended to come to a standstill without reaching 100 per cent. Here in consequence the same observation was made as was often reported when farm manure, compost, or green manure were used; part of the N became incorporated in stable fractions of the humus and seemed never to become decomposed.

Another interesting observation of Owen and collaborators is that the rate of mineralization of the more resistant proteinaceous products, expressed as percentage of the applied N, proved to be independent of the amount applied, whereas the mineralization of urea, guano, glycine, and the nitrification of $(NH_4)_2SO_4$ were inversely proportional to the rate of application. Apparently the ammonification of the proteins is so slow that even with the highest application the ammonia produced could not attain concentrations limiting the speed of nitrification, whereas the mineralization of the readily decomposed products, such as urea and amino acids, is limited by the nitrification capacity of the soil.

d. Green Manure. Nonleguminous plants have only incidentally been applied as green manure and their influence upon the mineralization of nitrogen has seldom been a separate subject of study. During recent years no important papers on this topic have been published. While still growing, such crops are not fundamentally different from other arable crops or grass leys and when plowed under, they have the same effect as crop residues, except that it is more pronounced. Much more important are leguminous green manures. The effect of incorporation of leguminous plants has been studied by innumerable investigators for more than 100 years. It is uniformly recognized now that leguminous plants, owing to their narrow C:N ratio, are decomposed in the soil much faster than other crop residues. As a result the following crop is more adequately supplied with nitrogen. Sometimes the mineralization is even too fast, with the consequence of considerable losses of mineral nitrogen through leaching or volatilization.

Fixation of nitrogen from the air by legumes is considered the main natural agency for replenishment of the level of N in soil depleted by crop removal and through losses by leaching and volatilization. Therefore it was presumed that leguminous crops would increase the total nitrogen (and perhaps also the total carbon) of the soil. But this expectation was not completely realized, and at present most investigators agree that cultivation of legumes often does not greatly raise the N_t or C_t levels of the soil. Apparently too much of the N of these plants is lost after mineralization. In contemplating the influence of legumes on the nitrogen balance of soil it never should be overlooked that these plants derive their nitrogen not only from the air but also from the soil, just as do nonleguminous plants. Many investigators long ago reported complete exhaustion of mineral nitrogen under growing legumes. Consequently the removal of much N in the leguminous crops, together with the fast mineralization of their residues, followed by considerable losses of the mineralized nitrogen, often proved responsible for a decrease of N_t in soil under legumes, instead of bringing about the expected gains. The better nitrogen nutrition of the crop following a legume, therefore, often must be considered the main beneficial effect of the use of legumes. The leguminous component of the sod of permanent grassland is recognized as a valuable agent in increasing the N_t of the soil, since such permanent grassland provides for rebinding of all nitrogen mineralized from the residues of the legumes.

Very clear and elaborate papers from the earlier literature, dealing with all the above-mentioned items, are the publications of Lyon *et al.* (1924), Löhnis (1926), and Pieters (1927). Some recent publications, however, provide valuable data about conditions in some special areas. Improved nitrogen nutrition of crops following legumes has been reported by Prescott (1934) for the Australian wheat belt. He mentioned better wheat yields after a leguminous crop. Smith and Mabbitt (1953) studied the effect of undersowing cereal crops by grass or clover and showed a significant beneficial effect. R. Newton *et al.* (1939), J. D. Newton *et al.* (1939) and Newton and Young (1940) claimed in the Canadian wheat-growing area higher yields and higher nitrogen content of the wheat for as long a period as three to four years after an alfalfa ley. They also reported complete exhaustion of all mineral N under growing alfalfa. During short periods of at most seven years of experiments they could not obtain a significant increase of N_t or C_t after alfalfa, but long-term observation of farmers' plots showed a marked retardation of the depletion of N_t, C_t, and humus. Schofield (1945) reported experiments with different tropical and subtropical legumes in the humid climate of the coastal area of Queensland in

Australia. Significant effect of the legumes on nitrogen nutrition could be demonstrated, but the decomposition was so fast under the humid subtropical climatic conditions that most of the mineralized N became leached from the upper 6 inches by the first heavy showers at the beginning of the wet season.

Kaila (1951, 1952a) and Kaila and Kivinen (1952) again studied the mineralization and nitrification of the organic N of leguminous crops. Generally their results agree fairly well with those of other investigators. Annual legumes such as peas and vetches increased the amount of mineral nitrogen only for a short period, and halfway through the following season higher nitrate contents could not be found, but the influence of clover leys was apparent for two years, or even more. They compared legumes with other additives (glucose, straw, farm manure, peat, etc.). Only the legumes gave an increase in mineral N, whereas all other substances more or less depressed the mineralization of N in the following year.

A paper by Greaves and Jones (1950) must be mentioned here separately, though their experimental work is open to criticism. They are even more conscious of the uptake of mineral nitrogen from soil by legumes than all other investigators. In their opinion the legumes increase the mineral N for the next year only by collecting much N in their roots, stalks, etc., in a readily decomposable form with a narrow C:N ratio. In this way they permit increased yields, but partly through exhaustion of the N from the soil. Greaves and Jones even claimed that legumes fix atmospheric nitrogen only when the supply from the soil is insufficient—an opinion certainly not tenable, since in many laboratory and pot experiments it was shown that the fixation of N from the air is maintained by the legumes even in substrates fairly rich in available nitrogen. But Greaves and Jones are certainly correct in their warning not to overestimate the effect of legumes on the enrichment of the N_t in soil. In their pot experiments significant gains in N_t could be attained only when the cultivated legumes were returned to the soil, whereas with the usual removal of the crop in the best case (lucerne) the N_t could be maintained. Their experiments were unfortunately performed under such exceptional conditions that the results cannot be applied to natural field conditions. Bjälfve (1952, 1953) and Kaila (1952a) fully realized the force of the above statements and therefore emphasized two ways for better utilization of the ability of legumes to fix atmospheric nitrogen, either by applying straw when plowing the land after a leguminous crop, thereby preventing the leaching of the surplus of nitrogen, or by applying straw before seeding leguminous crops, thereby fixing the available nitrogen and requiring

the legume to derive its nitrogen supply from the air. These lines of approach now more and more dominate farming practice in Scandinavia, resulting in a more economic use of nitrogenous fertilizers.

Some investigators have claimed a significant excretion of nitrogenous substances by roots and nodules of the *Leguminosae* (Virtanen, 1938; Virtanen and Torniainen, 1940; Virtanen and Laine, 1935, 1936; Virtanen *et al.*, 1937; Bjälfve, 1935; Nicol, 1934, 1936; Scholz, 1939; Madhok, 1940). However, other investigators could not confirm this observation (Wilson and Burton, 1938; Wilson, 1940; Ludwig and Allison, 1940). As a result a controversy arose, which led to an extensive study of this problem. A solution now seems to be found since positive results could be attained only under certain conditions, i.e., long days and rather low temperatures (Lyon, 1936; Wilson and Wyss, 1937; Bond and Boyes, 1939; Wyss and Wilson, 1941; Roberts, 1946). It is, however, still very doubtful whether this root excretion is of practical significance. But Katzelson *et al.* (1954) presented evidence of significant liberation of amino acids by the roots of wilted plants when the root environment was remoistened. This occurred both with nonlegumes and legumes.

In older publications it was shown that while annual legumes, such as peas and beans, contain maximally 5 to 12 per cent of the total N of the plant in their roots, this percentage is much higher with the leguminous ley plants (clovers and lucerne), and varies between 20 and 30 per cent (Mielck, 1913; Schneidewind and Meyer, 1914; Brown and Stallings, 1921; Headden, 1910). It is clear that this may explain why clovers and lucerne, even when normally harvested, prevent depletion of N_t in the soil, whereas annual legumes are not able to do so. Accurate data about the percentage of N in roots and stubble have recently been collected in Finland by Kaila (1952a) and by Salonen (1949), mainly confirming the other figures.

7. *Influence of the Level of pH and of Liming on Mineralization of Nitrogen*

The dominant influence of the reaction of soil on the mineralization of organic substances was recognized long ago. It is enough to recollect such classical investigations as those of Remy (1902), Ehrenburg (1904), Voorhees and Lipman (1908), and many others. At the same time it was also already understood that the last phase of the mineralization, i.e., the oxidation of ammonia, is even more hampered by an acid reaction than the ammonification, the latter still being slightly active even at pH levels around 4.0. Some cases of too abrupt and too drastic liming of acid, peaty soils, whereby the microflora was tem-

porarily destroyed and mineralization suppressed, have also been reported Lipman *et al.* (1909), but generally liming of acid soils was found to have a stimulating effect on the mineralization of humus nitrogen.

During recent years not many fundamentally new facts have been added to our knowledge of this topic. Confirmation of the well-known beneficial effects of liming has been given in some papers. Only the work of Allison and Sterling (1949), however, contains some observations of far-reaching importance. They used in their work only mineral soils with a pH level between 6.1 and 7.3, without an excess of calcium carbonate. Liming had in all cases a very stimulating effect on mineralization, which effect was maintained for a long time. Very interesting is their experience that, whereas in the original soils the amount of mineralized nitrogen per unit of N_t was found to be higher, the higher the N_t was, this difference was nearly leveled off after liming. This may perhaps be explained by the drop in the pH values of the unlimed samples during incubation (0.3 to 0.5 pH unit).

Cornfield (1953), using a nearly neutral clay soil (pH 6.65), studied the effect of artificial acidification to pH about 4.0 by addition of sulfur, $AlSO_4$, or $FeSO_4$. The over-all mineralization of nitrogen was significantly reduced thereby through a nearly complete suppression of nitrification; the ammonification decreased only slightly. Consequently NH_4 accumulated in the acidified samples. Liming these acidified soils practically restored the original conditions.

Collier (1953) studied the mineralization of the native humus and of different added nitrogenous substances in a calcareous clay soil and in an acid sandy soil. The whole process, and especially the liberation of mineral nitrogen, was much faster in the calcareous clay soil than in the sandy soil.

An elaborate discussion of the effect of liming upon the mineralization of nitrogen has also been given by Kappen *et al.* (1949) and Kappen and Scharpenseel (1951). Schachtschabel (1953) reported careful laboratory experiments on the effect of liming. The addition of lime resulted in an increase in nitrogen mineralization, varying between 100 and 1500 kg. of nitrogen per hectare. The effects of differences in the kind of lime were of minor importance.

That ammonification and nitrification are not necessarily correlated has been once more confirmed by Fraps and Sterges (1947), working in Texas soils with different pH levels with and without application of $(NH_4)_2SO_4$ and organic substances.

Hwang and Frank (1938) extended their investigation of the ammonification and nitrification in soils over a wide range of conditions

(reaction, moisture content, aeration, temperature) and formulated the important general rule that nitrification is much more restricted to optimal conditions than ammonification. Since ammonification is still significant in all extreme cases, the result is an accumulation of ammonia both at too high and too low pH, too high and too low temperature, and so on.

A paper on the mineralization of nitrogen in cultivated acid laterite soils of New South Wales was published by Parbery (1945). In these soils, containing 9 to 10 per cent organic matter, liming, just as in all other cases accelerated the mineralization, but even more so the nitrification, thereby increasing the NO_3 content but not the NH_4 content of the soil.

In 1939 Kalnins reported some long-term experiments on the mineralization of lupines. He mentions that addition of lime stimulated the development of the microbes and accelerated the formation of mineral nitrogen. Jolivet and Helias (1953a, b) observed in lysimeter studies on a sandy soil, high in humus, that liming with CaO stimulated the mineralization of organic nitrogen much more than when $CaCO_3$ was used in equivalent amounts.

In this review the nitrification process *sensu strictu* will not be dealt with. Therefore the influence of lime and of the reaction of the soil upon this process will be mentioned only briefly. The older investigators were mainly interested in acid soils, and soon much evidence was collected to show a very beneficial action of liming upon nitrate formation (Hall *et al.*, 1908; Temple, 1914; Arnd, 1919; Noyes, 1919; Nehring, 1929; and Fraps and Sterges, 1932). This opinion has in recent years been confirmed in different papers (Walker *et al.*, 1937; Hwang and Frank, 1938; Parbery, 1945; Halvorson and Caldwell, 1949; Allison and Sterling, 1949; and Stevenson and Chase, 1953). Some of the papers even claim a close correlation between the pH and the rate of nitrification with one type of soil (Stevenson and Chase, 1953).

The question of the optimal pH for nitrification has been the subject of many investigations and discussions. In older papers (Winogradsky and Winogradsky, 1933; Olsen, 1929a, b; Gaarder and Hagem, 1921; Nehring, 1929; Valmari, 1921; Tuorila, 1933) as well as in recent publications (Schmalfusz, 1936; Corbet, 1935; Turtschin, 1936; Caster *et al.*, 1942; Martin *et al.*, 1943; Jewitt, 1942; Parbery, 1945; and Halvorson and Caldwell, 1949) widely divergent pH ranges have been reported. Norman (1943) suggested as partial explanation for this disagreement a fixation of some elements, such as phosphorus, indispensable for the nitrate formers at high pH levels in desert soils, whereas in

nutrient solutions or artificial media these elements, are given in adequate amounts. However this hypothesis requires further proof. At the acid end of the range peat soils allowed nitrate formation at much lower pH levels than mineral soils (Kaila, 1954). Kaila even expresses as a hypothesis that in peat soils some, as yet unexplained, chemical oxidation of ammonia takes place.

Thus many problems concerning the influence of pH on nitrification still remain unexplained, but it is not possible here to enter further into these questions. We can say only that it is evident that pH limitation of the nitrification process depends on different conditions in the soil; it is not yet possible to give figures valid for all soils, though a slightly alkaline reaction seems to be optimal. Smith and Bell (1946–1947) observed a beneficial effect of liming and of boron on the nitrification in an acid light sandy soil in Florida, and Eno and Blue (1954), studying the nitrification of ammonia, observed that in acid soils anhydrous NH_3 is nitrified faster than $(NH_4)_2SO_4$, because NH_3 neutralizes the acid soils, whereas in neutral soils $(NH_4)_2SO_4$ is nitrified faster than NH_3, presumably as a consequence of too high temporary alkalinity around the place of injection of NH_3.

Brief consideration must be given to the formation and accumulation of nitrite in soils. It was recognized long ago that in most normal soils nitrite seldom accumulates to a measurable level, but some exceptions have been reported in the literature. In all these cases the pH was rather high, so it was understood that the formation of nitrite was more enhanced by a high pH level than the transformation of nitrite to nitrate. Fraps and Sterges (1947) mentioned that nitrite sometimes accumulated in soils when treated with lime or magnesium carbonate, while Drouineau *et al.* (1948) reported a considerable accumulation of nitrite in a soil very rich in carbonates (58 per cent CaO). In 1952 Chapman and Liebig published the results of their investigation of nitrite formation. They again confirmed the observation that accumulation of nitrite in soils happens especially under alkaline conditions, particularly after heavy fertilization with ammonia compounds or nitrogenous organic substances. Urea proved to be especially favorable for accumulation of nitrite. It was surprising that nitrite sometimes was rather persistent and remained in the soil for two to three months. Chapman and Liebig never came across formation of nitrite from nitrate through denitrification.

8. Influence of Sterilization of Soil on the Mineralization of Nitrogen

The study of the influence of a partial sterilization of the soil on the liberation of plant nutrients is already old and the "partial sterilization effect" is a well-known phenomenon. The older literature refers

mainly to steam sterilization, whereas in recent years the effect of modern herbicides, insecticides, fungicides, and growth-regulators has been more and more investigated.

Papers dealing with the effect of steam sterilization are rather scarce in recent years. Malowany and Newton (1947) published an elaborate study on this subject, confirming the old experience that steam sterilization increased the ammonia concentration in the soil during the first four to six weeks after treatment. Thereafter the ammonia content, rapidly decreased to the normal level with a simultaneous increase of the nitrate content. It was remarkable that, in spite of reinfection of the steamed soil by unsteamed, the nitrification remained suppressed for so long a period, but then at once jumped up. The more humus in the soil, the more pronounced was the effect of steaming.

Kidson and Stanton (1948) compared the effect of steam sterilization with that of some chemicals (D.D., gammexane, and chloropicrin). All these treatments produced the well-known "partial sterilization effect." The effect of the least volatile, chloropicrin, was maintained about two months longer than that of steaming.

Oxley and Gray (1952) studied in detail the microflora of steamed soils, especially trying to describe the microbe associations characteristic in the first period with the rapid formation of ammonia and in the second period with the nitrification.

The experience of Roll-Hansen (1952) was approximately the same as that of most other investigators; a sharp increase of the microbial activity and of the formation of ammonia was followed by a rapid fall of the microbial numbers and by a rapid nitrification of the ammonia.

A very careful and elaborate study was published by Davies and Owen (1951, 1953, 1954) on the steam sterilization of glasshouse soils. The main results of their work are: (1) Part of the ammonia in some soils was liberated during steaming by a chemical hydrolysis. (2) Ammonia production increased with the duration of steaming. (3) When steamed soil is kept undisturbed the high content of ammonia is maintained for a long time, but aeration of the soil rather soon initiates nitrification. (4) Contamination of steamed soil by unsteamed also accelerates the onset of nitrification. (5) Cultivation of a crop also accelerates the beginning of nitrification. (6) Part of the ammonia liberated during steaming seems to be formed at the cost of nitrate in the original soil. (7) A second steaming proved to have much less effect than the first. All these results may be considered as proved, especially since they agree well with many earlier observations.

Kaila *et al.* (1953) applied steaming and dry heating to peat soils.

In peat soils any type of heating had a pronounced effect and brought about very high ammonia contents. Even temperatures of only 50° to 75° C. had a marked effect of this sort.

A "partial sterilization effect" similar to that of steaming was long ago observed with the application of various antiseptics. An extensive literature has therefore accumulated on this topic, but most of these workers only superficially, if at all, studied the effect of these treatments on the mineralization of nitrogen, which as a rule is less pronounced than after steaming.

Nilsson (1951) found drastic suppression of the nitrification capacity of soils after treatment with sodium chlorate. Kidson and Stanton (1948) and Kidson (1948) observed a long but not very pronounced "partial sterilization effect" when soil was treated by D.D. or by chloropicrin. Smith *et al.* (1946) checked the effect of 2,4–D (dichlorophenoxyacetic acid) on the soil. Low concentration had no visible effect but concentrations of 100 p.p.m. or more displayed a weak sterilization effect without an appreciable increase in ammonia production. The nitrifying organisms proved to be very sensitive to 2,4–D.

Newman (1948) studied the effect of some of the modern herbicides (2,4-dichlorophenoxyacetic acid, 2,4,5-trichlorophenoxyacetic acid, 2-methyl-4-chlorophenoxyacetic acid, isopropyl-*N*-phenyl carbamate) on the microflora of soil and especially on nitrification. Only concentrations far beyond those applied for weed control suppressed the microflora, especially in acid soils. The nitrifying organisms again proved to be the most sensitive group. The results obtained by Koike and Gainey (1952) are slightly different; 2,4–D and Cadé were found to exhibit a marked bactericidal action even in concentrations applied for weed control, and to cause afterwards a temporary increase in bacterial numbers and in ammonia content in the soil. The nitrification process was suppressed for a period of two to four months.

Some insecticides have also been studied recently. An investigation of the bactericidal effect of benzenehexachloride was performed by Gray (1954). Only concentrations beyond what is necessary for practical application proved to have a "partial sterilization effect." Smith and Wenzel (1948), however, found a more marked suppression of the microflora and especially of the nitrifying bacteria with benzenehexachloride. Chlordane and D.D.T. were less harmful for microbes when applied in practical dosage.

Smith and Bell (1946–1947) reported some observations on light sandy soils in Florida. D.D., chloropicrin, D.D.T., and 2,4–D all exhibited for a short while a "partial sterilization effect." D.D.T. and 2,4–D had the strongest effect, lasting for some 70 days. They used

also different concentrations of copper sulfate. Only large amounts (100 pounds per acre) showed a depression of the microflora, whereas 25 pounds per acre even stimulated nitrification for a month. In summary, it must be concluded that the researches on the effects of modern fungicides, insecticides, herbicides, and growth-regulators on the soil microflora and on the mineralization of nitrogen are still very fragmentary, with numerous contradictions. More work will be needed to be able to decide whether any of these treatments may eventually have adverse effects on the metabolism in soil.

An entirely different type of a "partial sterilization effect" has been studied during World War II and in postwar years in Holland, where old farmland on a large scale was flooded by sea or brackish water as a result of warfare or of exceptionally high floods damaging the dikes. The microflora of the old farmland was adversely influenced and changed by the sea water, but recovered rapidly after restoration of the dikes and re-establishment of normal conditions. This was accompanied by an unusually luxuriant development of microbes and a distinct "partial sterilization effect." One of the important results thereof was a significant increase in the mineralization of nitrogen, lasting for about a whole season. This exceptional ammonia formation might be partly a result of an exchange of NH_4 ions from the crystal lattice in the clay minerals by the excess of Na ions of the sea water, but during the later stages of the drainage and recovery of the soils this definitely cannot be the correct explanation, and an enhanced mineralization of nitrogenous organic substances must be presumed. This nitrogen effect, being first observed on the isle of Tholen in the province of Zeeland, was given the name of "Tholen effect," well known to all farmers in that district. A short paper dealing with this subject appeared in 1944 (Harmsen), and a more elaborate study is now in press (Harmsen, 1955b).

III. The Fate of Mineralized Nitrogen in Soil and Causes of Losses

For a correct interpretation of nitrogen metabolism in soil it is important to study not only the process of mineralization of nitrogen but also the later fate of the different nitrogenous compounds formed in the consecutive stages of the mineralization process. The last of these stages, the true nitrification, is intentionally not included in this review, but the products of the other processes will be mentioned briefly.

The first stage of the decomposition of proteins in the soil is their breakdown by hydrolysis and decarboxylation to amino acids and amines by means of microbial enzymes. These products may be: (1) further broken down to ammonia by transaminase and deaminase sys-

tems, (2) fixed to clay minerals and lignin, thereby temporarily or permanently becoming inert and resistant to further decomposition, or (3) absorbed by higher plants. If much available carbon is present none of these products will ever accumulate in the soil, as the greatest part of the amino acids will immediately again be metabolized by soil microbes, and higher plants sometimes may also indirectly take up amino acids by means of ectotrophic mycorrhizae. However, no transport of nutrients from endotrophic mycorrhizae into the plants was observed by Winter (1953).

1. Decomposition and Fixation of NH_2 and NH_4 Groups

Bremner (1950b) has shown that part of the humus complex consists of amino acids present in the combined state, but he failed to detect free amino acids in cold aqueous extracts of several neutral clay loams and fen soils which were concentrated at low temperatures *in vacuo* and examined by paper chromatography. In further work, with acid peats, however, several faint spots were observed by Bremner (1952) on chromatograms of aqueous extracts, and serine, glycine, alanine, aspartic acid, and glutamic acid could be identified. The amounts of free amino acids detected were very small, however, and according to Bremner it does not appear likely that more than traces of free amino acids occur in normal agricultural soils. Using paper chromatographic techniques Dadd *et al.* (1953) found free amino acids in nine soils examined, but the amounts again were small. These soils were mostly organic, taken from under natural vegetation, covering a wide range of acidity and of associated humus types. The results suggest that there may be a seasonal difference in the number and concentration of free amino acids, and that an inverse relationship may exist between soil pH and the total concentration of free amino acids in the soil solution.

Using the method of Sanger (1945), Sowden and Parker (1953), however, failed to find free amino groups in soils studied or in organic fractions isolated from them. It may consequently be concluded that free amino acids occur in ordinary soils only in minute concentrations, the more so since most amino acids are rapidly mineralized when percolated through soil in the technique of Lees and Quastel. Lees with his collaborators extensively studied this problem using the "stimulated soil" modification of his technique (Lees, 1946, 1947, 1948c, 1952a, b; Quastel, 1950; Lees and Quastel, 1944, 1945, 1946c; Quastel and Schole-field, 1949, 1950, 1951; Owen and Winsor, 1950b; Jensen, 1950b; Tombesi, 1953; Lees and Porteous, 1950a, b; Gleen, 1951). The main purpose was to check whether only NH_4 is subject to oxidation to nitrite by *Nitrosomonas* or whether some amino acids and other soluble com-

pounds containing NH_2 groups can be oxidized. With such columns the relation of the nitrification of ammonia and time is linear. If other substances showed the same linear relation, it would point to direct nitrification of these products by the same nitrifying organisms (*Nitrosomonas* and *Nitrobacter*), whereas the necessity for their prior decomposition with the liberation of ammonia would be revealed by a sigmoid curve. Despite the wide variety of nitrogenous compounds tested (Kermack and Lees, 1952; Lees, 1952a, b, 1948d; Jensen, 1950a), none, except ammonia and perhaps hydroxylamine in very low concentrations, proved to be directly converted to nitrite by *Nitrosomonas;* this is in agreement with older opinion. During all these investigations the authors observed that most amino acids were readily mineralized by the soil microflora, with the exception of methionine and cystine (Quastel and Scholefield, 1949; Owen and Winsor, 1950b), but in many cases only low concentrations were tolerated by the microflora, and higher concentrations proved to be toxic. The mineralization of amino acids does not increase the acidity, as happens when ammonium salts are nitrified (Quastel and Scholefield, 1950). Oximes proved also to be easily nitrified. These authors also studied the inhibitory effect of many organic and inorganic substances on the nitrification of ammonia and on mineralization of amino acids. Many of the inhibiting substances belong to the class of chelating agents, presumably because they inhibit the action of metal enzymes.

In the process of humus synthesis much of the NH_2 and the NH_4 nitrogen can become incorporated in the humus molecule. It is especially Mattson and Koutler-Anderson (1942, 1943) who pointed to the importance of this fixation of nitrogen to lignin-complexes in the process of humus formation in soil. The ammonia and amine groups are so strongly fixed to the humus molecule that they cannot be released by alkalies or weak oxidation reagents. The humus becomes more resistant the more oxygen and ammonia or NH_2 groups are fixed.

However, this humus formation theory of Mattson has been severely criticized; it can represent only one of the ways of humus formation (Sowden and Atkinson, 1949). But in the modern concept of humus synthesis, the formation of "humic acid" and "melanoidins" (Laatsch, 1948a, b, 1950; Laatsch *et al.*, 1950, 1951; von Plotho, 1940, 1947, 1950; Scheffer *et al.*, 1949; Enders and Theis, 1938; Enders, 1938, 1942, 1943a, b; Enders and Sigurdsson, 1943; and many papers from the school of Flaig), NH_2 and NH_4 groups also are presumed to be present, thereby explaining its generally high content of nitrogen. The extensive literature on humus synthesis, however, falls beyond the scope of this review. A discussion of some of these theories and of their

influence on the whole problem of humus formation and N transformation was given by Norman (1943).

The absorption of free NH_2 groups by clay minerals has scarcely any importance. Much more significant is the formation of complex compounds of proteins or their decomposition products with soil minerals. But this subject again lies more in the field of humus chemistry than in that of mineralization of nitrogen. Therefore only some of the more important contributions in recent years will be mentioned here. Apart from the older German and Russian work, this process has been studied by Laatsch (1951), who found a significant protection of proteins against decomposition by some clay minerals. The stabilization effect of clay minerals had earlier been pointed out by Meyer (1935, 1941). Siegel and Meyer (1938) emphasized the addition of montmorillonite clay to heaps of stable manure to aid in retention of nitrogen.

The binding of organic compounds to clay minerals has been studied by means of the electron microscope by Kroth and Page (1947), and recently by Flaig and Beutelspacher (1951). An important part of the nitrogen in the soil proved to be present as amino nitrogen. Kojima (1947a, b) and Bremner (1949a, 1950a) report amino-N contents of 33 to 37 per cent of the total nitrogen. According to Wittich (1952) the values range from 29 to 60 per cent of the total nitrogen in different German soil types. The lowest contents were found in podzols, the highest in rendzinas. Schlichting (1953) found low values for heath soils. In different fractions of humates of three Canadian soils investigated by Parker *et al.* (1952), the amino N content in a black soil ranged from 12.5 to 27.2 per cent, in a brown prairie soil from 18.6 to 39.6 per cent, and in a podzol soil from 24.2 to 29.9 per cent, calculated as per cent of total nitrogen. In the organic fractions several types of amino acids were determined by paper chromatography. These fractions differed from plant proteins in that no sulfur-containing amino acid and very little arginine and histidine were formed. Evidently comparatively important amounts of amino acids derived from albuminoid compounds may be present in the soil, as pointed out by Laatsch and Schlichting (1953). If this is true the other proteinaceous substances probably are protected against microbial attack by the formation of complex compounds with mineral soil constituents. Ensminger and Gieseking (1939, 1942) indeed found an increase in resistance of proteins against proteolysis in the presence of clay minerals. The work of Allison *et al.* (1949) and of Goring and Bartholomew (1952) must be mentioned in this connection. They studied the absorption of mononucleotides, nucleic acids, nucleoproteins, and other proteins by different clays and clay minerals. Nucleoprotein acid derivatives are con-

sidered to be among the most important organic compounds in the soil. They are absorbed most strongly between pH 1 and 4; the absorption decreases between pH 4 and 8, and above pH 8 no absorption takes place. However, much of the NH_2 nitrogen found in soil is derived not from plant proteins absorbed by clay minerals but from the final stable humus.

2. Uptake of Amino Acids and Amines by Higher Plants

During the last few years it has been proved in aseptic cultures that a number of amino acids and lower aliphatic amines may directly be assimilated by higher plants, as was presumed by various earlier investigators, but the capacity of uptake depends on the plant species and on the type of the substance. For the older literature on this subject we refer to Brigham (1917) and Ghosh and Burris (1950). Virtanen and Linkola (1946) found that both the D and L forms of aspartic and glutamic acids are assimilated by peas and clover; they are taken up by the plants, and if aspartic acid, nitrate, and ammonia are supplied together, they are utilized simultaneously. Wheat and barley, however, were unable to use aspartic or glutamic acids as nitrogen sources. Spoerl (1948) found that only L-arginine was used by young orchid embryos under aseptic conditions, whereas 18 other amino acids were not assimilated. In aseptic cultures Ghosh and Burris (1950) observed that clover and tomato showed considerable similarity in their response to organic nitrogenous compounds. The development of tomatoes was stimulated by DL-glutamic acid, L-glutamic acid, glycine, L-histidine, L-leucine, L-arginine, L-cysteine, and L-lysine. Clover was able to use DL-alanine, L-arginine, L-asparagine, DL-glutamic acid, glycine, and L-histidine. Tobacco was much more sensitive to amino acids, and several of them inhibited its growth. Analysis of the N^{15} content of clover and tobacco plants simultaneously furnished with $N^{15}H_4^+$ and single amino acids indicated that generally the plant first uses its reserve of seed nitrogen, then ammonia, and finally the amino acids.

The effect of amino acids on growth of tobacco also was studied by Steinberg (1947) and by Pratesi and Ciferri (1946). They observed toxic effects of a number of amino acids. The control medium with nitrate and ammonium ions produced better growth than did single amino acids. Depression of growth of excised tomato roots by certain amino acids was observed by White (1937), studying the effect of a variety of amino acids and other compounds on the growth of (*Nasturtium officinalis*). Audus and Quastel (1947) found that all amino acids tested, except alanine and glutamic acid, inhibited root growth at a concentration of 1,000 p.p.m.

From the results reported it seems likely that a number of free amino acids formed in the soil may be used by higher plants if in low concentration. Two papers must, however, be mentioned: Bonner (1946) and Swaby (1942). The authors of both arrived at the reverse conclusion, namely, that the uptake of organic substances by roots of plants must be considered very doubtful under aseptic conditions. A very clear, critical, but incomplete review of this subject has recently been given by van Raalte (1954), who leaves the question open whether organic substances can be utilized by plants without the aid of microbes.

3. *Availability of Ammonia in Soil*

The ammonia formed when amino acids are decomposed by microorganisms may be (1) utilized by higher plants, (2) used for the synthesis of humus during decomposition and oxidation of lignin, as has been discussed in the previous paragraph, (3) absorbed by clay minerals or humus, or oxidized by nitrifying bacteria.

An accumulation of ammonia is possible only when no surplus of readily utilizable carbohydrates is available. Though this remark is not specific for ammonia but is also applicable to all forms of soluble nitrogen, some observations definitely point to a preferential utilization of ammonia by microbes. Richards and Shrikhande (1935) reported such observations, and recently Jansson *et al.* (1955) presented a very interesting paper dealing with the same subject. Using the tracer technique they could demonstrate much faster utilization of ammonia-N during decomposition of oat straw or corn stalks than of nitrate-N, both in artificial media and in soil, and at all pH levels and moisture contents. The decomposition of the straw was much faster with ammonia-N than with nitrates. The authors correctly concluded from these experiments that ammonia fertilizers must be considered superior to nitrates for rapid decomposition of straw during preparation of artificial manures or composts with optimal conservation of nitrogen.

This behavior of microbes (bacteria as well as fungi) contrasts sharply with the old and many times confirmed experience that higher plants, though being able to assimilate ammonia, definitely prefer nitrates. However, trees, shrubs, and grasses are often forced to use ammonia, since the formation of nitrates proceeds insufficiently in acid forest and grassland soils. Azaleas and other plants, which prefer an acid medium, and species growing in waterlogged soils also prefer ammonia-N to nitrate-N.

Although the absorption of free amino acids and amines by clay minerals is of minor importance, the NH_4-ion is readily absorbed on the surface and in the crystal lattice of many soil minerals, whereby its availability for uptake by plants and microbes and for nitrification is

considerably reduced. Ammonia, consequently, can become fixed by clay minerals as well as by the organic substance in soil and by the microflora.

The problem of the availability of ammonia for plant nutrition will be discussed in Section IV. However, it may be mentioned here that all recent studies on the accessibility of ammonia for nitrification arrived at the conclusion that in most soils only a minor part of the total amount of NH_4-ions is available for nitrification, varying between none and about 30 per cent (Albrecht and McCalla, 1938a, b; Kingma Boltjes, 1935; Pathak and Shrikhande, 1952; Bower, 1951; Allison *et al.*, 1951, 1953a, b).

An opposite effect of absorption on the availability of NH_4-ions for nitrification has been found by Lees and Quastel (1946). By means of the percolation technique they showed that the rate of nitrification is a function of the degree of absorption of NH_4-ions on the absorption complex of the soil. The greater the amount of absorption, the faster is the rate of nitrification. It was even more spectacularly shown by the fact that when a soil was percolated with a solution of ammonium sulfate, little or no nitrification takes place in the percolating solution, and by the fact that the rate of nitrification is diminished in proportion to the amount of NH_4^+ displaced from the absorption complex by base exchange with Ca^{++}. Lees and Quastel therefore concluded that the absorbed ammonium ions are preferentially nitrified by the soil organisms. The interpretation of these results might be that the nitrifying bacteria grow on the surface of the soil particles just where ammonium ions are held in base exchange combination and proliferate at the expense of such absorbed ammonium ions (Quastel, 1947). The rate of proliferation becomes proportional, therefore, to the area of soil surface on which ammonium ions are absorbed, and is therefore a function of the base exchange capacity of the soil. However, this explanation is open to criticism. Pathak and Shrikhande (1952) later confirmed the observation of Lees and Quastel, by increasing the rate of nitrification in a solution by addition of clay suspension. This effect of the absorption of NH_4-ions is not in conflict with the above-mentioned unavailability of the greatest part of absorbed ammonia to the nitrifying organisms, since the beneficial effect of the absorption complex bears only upon the loosely absorbed and readily exchangeable ions of ammonia on the surface of the clay minerals.

Thus, the availability of ammonia in soil depends in a rather complex way on the fixation power of clay minerals and humus, and on the presence of other competing cations in the absorption complex. It is not known whether the nitrogenous substances extracted from soil by hot water, or by 2 per cent HCl, subsequent to an extraction with

cold water, found by Barnes (1953), represent mainly ammonia, but this may be presumed. This less readily extractable fraction of N proved during long incubation experiments to remain remarkably constant and unaffected by the increase of water-soluble nitrogen. It, therefore, seems improbable that these fractions are intermediate stages in the decomposition process.

4. *Different Sources of Losses of Mineralized Nitrogen from Soil*

The forms of mineralized nitrogen most liable to losses are the nitrites and nitrates, since these compounds, though being readily used by plants and microbes, are not absorbed by any part of the soil and consequently are easily leached out by precipitation, as has already been discussed in Section II. But nitrates, nitrites, and ammonia can suffer losses from soil in some other ways.

a. Losses through Denitrification of Nitrates. As already stated in the introduction, denitrification will not be discussed here. Attention may be drawn to a series of interesting papers dealing with the fundamental aspects of the denitrification process, published during the last few years by the school of Kluyver at Delft (van Olden, 1940; Sacks and Barker, 1952; Verhoeven, 1952; Allen and van Niel, 1952; Kluyver, 1953; Verhoeven and Goos, 1954; Kluyver and Verhoeven, 1954a, b; Verhoeven *et al.*, 1954; Baalsrud and Baalsrud, 1954).

Furthermore the investigations of Verhoeven, Korsakova (1927, 1941), Meiklejohn (1940), Corbet and Wooldridge (1940), Jansson and Clark (1952), Jones (1951), and Marshall *et al.* (1953) have definitely demonstrated that dentrification is not necessarily restricted to anaerobic conditions, but quantitatively it becomes important in normal soils only when the aeration is considerably reduced, or when the soil is rich in organic substances with a low C:N ratio (Jansson and Clark, 1952; Broadbent, 1951; Broadbent and Stojanovic, 1952).

b. Losses of Elementary Nitrogen from Aerobic Acid Soils. Another possibility of escape of nitrogen in gaseous form is observed in acid soils rich in humus. In such a soil when nitrites come in contact with ammonium salts, with amines, or even with nitrogen-free sulfur compounds, elementary nitrogen is formed. The suggested mechanism, mentioned by Wilson (1943), Allison and Sterling (1948), Allison and Doetsch (1951), Allison *et al.* (1952), and recently by Wijler and Delwiche (1954) can be expressed by the following overall reactions:

$$RNH_2 + HNO_2 \rightarrow ROH + H_2O + N_2 \nearrow$$

or

$$RNH_4 + HNO_2 \rightarrow RH + 2H_2O + N_2 \nearrow$$

This process may occur in well-aerated acid soils. Addition of ammonium sulfate to slightly acid soils therefore may sometimes result in losses of gaseous nitrogen. It was found by Gerretsen (1949, 1950) that the conditions which favor these losses are vigorous nitrification, a sufficient local concentration of ammonium sulfate, and a buffering capacity which maintains the pH between 5.5 and 4.5 during nitrification. However, in chemical studies by Allison *et al.* (1951), conducted in Warburg respiration vessels, it was shown that nitrous acid can react with an amino acid, such as alanine, to form nitrogen gas at pH values of 4.5 and lower. Under the experimental conditions the percentage of the added nitrite that reacted in 5 hours varied from 1.2 at pH 1.6 to a maximum of 5.8 at pH 3.4. No gas was evolved at pH 5.2 or higher.

The above-mentioned reaction, that in normal conditions is never of practical importance, in some cases can even be opposed by an oxidation of nitrite, as described by Corbet (1935), Turtschin (1936), Fraps and Sterges (1939b), Gerretsen (1949, 1950), and Allison and Doetsch (1951). In some acid soils this oxidative liberation of nitrogen can be rather important; Allison (1955) even considers this way of loss to be the most important.

Under anaerobic conditions Jones (1951), using tracer technique with N^{15}, found only negligible amounts of nitrogen evolved; this probably was the result of the activities of denitrifying bacteria.

c. Losses of Nitrogen through Volatilization of Ammonia. A third, and presumably most important, source of loss of nitrogen is through volatilization of ammonia from the surface of the soil. When materials containing or yielding ammonia, are applied to the soil, the greater part of it is absorbed at or near the surface (Jenny *et al.*, 1945). In an alkaline soil, however, part of the ammonia will be present as ammonium carbonate, bicarbonate, or hydroxide, depending on the alkalinity, concentration, and other factors. From aqueous solutions of these compounds the ammonia will evaporate at varying rates, depending on the concentration and character of the ammonium containing solutions.

For the older literature dealing with this problem the reader is referred to Tovborg-Jensen and Kjaer (1948, 1950). The modern contributions can be split into two different subjects: losses from organic and those from inorganic compounds.

(1) Losses of ammonia from organic materials. In laboratory experiments by Sreenivasan and Subrahmanyan (1935) it was found that the loss of nitrogen as NH_3 from waterlogged soils to which had been added high amounts of dried blood or urea was much greater than

from soils maintained at 60 per cent saturation. High losses of nitrogen by volatilization of ammonia from flooded soils was also found in laboratory experiments by Willis and Sturgis (1945). A decrease in H-ions concentration increased the loss of nitrogen. Losses of ammonia may occur even in an acid soil high in organic matter where ammonia is liberated by decomposition, as was shown in Section III, 4*b*, but in a soil low in organic matter and with a high exchange capacity a considerable amount of ammonium nitrogen may be absorbed even at relatively high temperatures and at reactions near or even slightly above neutrality.

In soils in Petri dishes to which were added 1 per cent of various organic substances, Pochon and Tchan (1947) found that samples which lost the greatest amount of ammonia through volatilization were also those with the greatest number of actinomycetes.

Using soils with various humus contents and treated with 1.2 per cent dried blood, Pochon *et al.* (1947) showed that losses of ammonia decreased with increasing humus contents. Barnes (1953), who used a soil with pH about 6, with addition of ground mustard plants, tare plants, straw, or ammonium sulfate, could detect a loss of nitrogen only when ammonium sulfate was added. In laboratory experiments by Pinck *et al.* (1950) losses of nitrogen from organic materials incorporated in soil to supply 1 per cent carbon in all cases, were insignificant if the C:N ratio was 18 or wider. As the ratio narrowed from 15 to 3 the losses became increasingly higher.

It is evident that all these investigations clearly point to a volatilization of NH_3 not directly from the organic substances but from free ammonia, after ammonification.

(2) Losses of ammonia from inorganic fertilizers. In laboratory experiments by Jewitt (1942) significant volatilization of ammonia was found when ammonium sulfate was added to alkaline soils (pH 8 to 10). No loss of nitrogen was found in a soil with pH 7. The basic factors revealed by these experiments are the paramount influence of the total quantity of ammonium salt present, and the close relationship between the loss of ammonium and the loss of water. The moisture content itself did not appear to be important. Loss of ammonia ceased when there was no loss of moisture. Barnes (1953) observed in incubation experiments a loss of *ca.* 30 per cent of the nitrogen added to soil samples as $(NH_4)_2SO_4$ within 89 weeks of incubation at optimal aeration in a soil of pH 6.0. However, it is not known assuredly whether this loss occurred through volatilization of ammonia.

Studies by Steenbjerg (1944) showed that losses of ammonia from soils supplied with ammonium sulfate ranged from approximately 5

per cent at pH 6 to 60 per cent at pH 8 in four weeks. This loss was almost eliminated when the fertilizer was covered with 6 cm. of soil. It was found by Jackson and Chang (1947) that volatilization of ammonia was greatly reduced when anhydrous ammonia was injected at a 2- or 4-inch depth.

Tovborg-Jensen and Kjaer (1948, 1950) concluded from their laboratory experiments that the rate of ammonia evaporation is directly proportional to each of the following factors:

1. Size of the contact surface between the soil and the atmosphere, which depends chiefly upon the structure.
2. The saturation deficit of the air with regard to NH_3.
3. The ammonia vapor tension—p_{NH_3}—in the soil, which depends on the total concentration of the ammonium salt and on the hydrogen ion concentration.

It was found that the risk of nitrogen loss increases with the temperature of the soil, the pH, and the content of $CaCO_3$, and with a decrease in moisture content. Clay and humus colloids absorb ammonia and may thereby prevent its volatilization even on soils with an alkaline reaction. At pH values below 6 no measurable loss occurred. Only from soils with pH values above 7 is it likely that volatilization losses may be economically important, but they may be reduced by harrowing the fertilizer into the soil and by applying it during or before rainy weather.

Martin and Chapman (1951) reported that below pH 7.2 very little ammonia was lost from ammonium sulfate or ammonium nitrate. On the other hand, slight losses from NH_4OH occurred even when the hydroxide was added to acid soils (pH 4.5), as a consequence of the temporary alkalinity created by addition of this solution. They also found that increasing the amount of ammonium nitrogen applied to an alkaline soil, augmented the total quantity of nitrogen lost but did not appreciably affect the percentage lost. The moisture content of the soil had little effect, but evaporation of water was necessary for volatilization of ammonia from soil. Losses increased with increase of temperature.

Since 1934 it has been known that on the calcareous soils of the Zuiderzee polders in the Netherlands nitrate-containing fertilizers generally have a better effect than ammonia-containing fertilizers. It was shown by van Schreven (1950, 1955) that appreciable amounts of ammonia may be lost by volatilization when ammonia-containing fertilizers are added to these soils. The rate of volatilization decreases with an increasing water content of the soil; therefore under field conditions loss of ammonia may be great on sandy soils. Moreover, the low absorption power of sandy soils favors the loss of ammonia. Even when

the fertilizer is harrowed into the upper layer of the soil, significant amounts of nitrogen may be lost by evaporation. However, evaporation is practically wholly prevented when the fertilizer is placed in a furrow at least 5 cm. deep and immediately covered with soil. It was shown that evaporation of ammonia after top dressing with ammonium sulfate is a general phenomenon in soils with a pH of 7 or higher and is not restricted to the newly reclaimed Zuiderzee. Independently of these experiments it was shown by Gerretsen (1950) that loss of nitrogen due to volatilization of ammonia after a top-dressing with ammonium sulfate occurs on soils containing more than 6 per cent calcium carbonate.

It was also found by van Schreven (1950) that the loss of ammonia depends on the kind of ammonium fertilizer. The rate of volatilization of ammonia from sulfate proved to be much greater than from nitrochalk or form ammonium nitrate when equivalent amounts of NH_4-nitrogen were supplied in the fertilizers. In further experiments (not yet published) it was found that the moisture content of the air may influence the evaporation of ammonia when the soil surface is very dry. In that case formation of dew during the night may promote evaporation of ammonia. The loss of ammonia may be decreased by treating the soil with humic acid, whereby the pH is lowered and the absorptive power of the soil increased.

To summarize all investigations about volatilization of NH_3 from soil it can be concluded that this loss of nitrogen achieves a level of economic importance only on calcareous soils and only when ammonia-containing fertilizer are used. NH_3-losses from ammonia formed by mineralization of organic compounds in the soil practically never became significant since the concentration of free—not absorbed—ammonia hereby seldom arises to a sufficiently high level.

Finally three papers must be mentioned which report considerable losses of nitrogen, without definitely attributing it to one of the above-mentioned processes. A lysimeter experiment by Chapman *et al.* (1949) showed that in addition to losses through leaching, rather large quantities of nitrogen were lost presumably by gaseous volatilization, though the mechanism involved remained unknown. Likewise losses of nitrogen, presumably as gaseous nitrogen, were observed by Mann and Barnes (1951) in pot experiments with two successive barley crops. No more than 40 to 51 per cent of the added nitrogen could be accounted for at the end of the experimental period (after 18 months) under well-aerated conditions. Doughty *et al.* (1954a) also reported considerable volatilization of nitrogen from brown prairie soils in pot and field

experiments, not through evaporation of ammonia. The subject of nitrogen balances in soils is discussed in more detail in the chapter by Allison in this volume (page 213).

IV. Determination of the Mineralization of Nitrogen in Soil

Though the availability of nitrogen for plant nutrition often is rather narrowly correlated with the amount of total nitrogen in the soil, as has been discussed in Section II,5, it was long ago recognized that determination of the total nitrogen has scarcely any value as an expression of the availability of nitrogen for crops. The older agriculturists and soil scientists therefore tried to determine the need for nitrogen fertilization by analysis of the soil for mineral nitrogen. But it was soon recognized that the content of mineral nitrogen in soil fluctuates over a very wide range and is influenced by many external factors (season, weather conditions, plant growth, fertilization, etc.). Innumerable investigators arrived at this conclusion. Recently it was again confirmed by: Hardy (1946), Harmsen and Lindenbergh (1949), Rappe (1950), and Kaila (1952a). So it is now widely recognized that the content of mineral nitrogen found at a given time does not provide helpful information about the need for nitrogen fertilization. The only property that may be expected to correlate with availability of soil nitrogen to plants is the rate of mineralization of organic substances in the soil.

One of the latest efforts to use the determination of mineral nitrogen at a particular time for estimating the need for nitrogen fertilization was the work of König and Hasenbäumer (1924). They claimed to have observed a rather good correlation between the content of mineral nitrogen found in soil extracts and the nitrogen requirement of the crops. Dirks and Scheffer (1928), however, compared the method of König and Hasenbäumer with the vegetation method of Mitscherlich and arrived at the conclusion that the König procedure may perhaps assess soils poor in nitrogen, but his method gives no information about the need of nitrogen for the crops. In the same year, however, Goy (1928a, b), and König (1929) once more obtained satisfactory results with the method of König and Hasenbäumer. In 1932 Nemec and Koppová published the results of an elaborate study. Their results are rather obscure; only in some of their experiments did they find some relation between the amount of soluble nitrogen and the response of the crops to nitrogen dressings. It therefore is surprising that Nemec, who in his earlier work (Nemec, 1926) used incubation methods, at this time attached some value to the determination of the content of mineral nitrogen in the soil at the moment of sampling.

1. *Short Review of the Different Methods*

From the many older publications and from the above-mentioned later efforts to use the determination of the momentary amount of mineral nitrogen in the soil for the estimation of nitrogen requirement for the crop, the conclusion may be derived that this method has only a very dubious value. This review therefore can further be confined to the discussion of different ways of determination of the rate of mineralization of organic nitrogen. These methods can be subdivided into three groups: field trials, pot experiments, and different procedures of incubation of soil samples under laboratory conditions. Each of these approaches to the problem has advantages and disadvantages. Field trials, to begin with, being the most direct empirical method, provide reliable results, but they are laborious time- and space-consuming, and subject to uncontrollable external influences such as climatic conditions, variation between seasons, influence of crops, and treatments of previous years. The number of reports about field nitrogen-fertilization experiments of course is endless, and since all these performances may be considered strictly empirical and agricultural in character, they need not be discussed in this review. Only the correlation between the crop yields, determined in field trials, with the results of incubation experiment will repeatedly be mentioned in the following pages.

Ordinary pot experiments may be compared with field trials. They, therefore, are fundamentally affected by the same shortcomings as the field trials, though the external conditions can now be better standardized. Pot experiments therefore also will not be discussed here, except when the N is analyzed regularly in the soil. Such pot experiments can be considered to be a modification of the incubation technique. So the following discussions will be devoted exclusively to the different types of incubation—or mineralization—experiments, by many writers designated as "nitrification" experiments, as the most suitable laboratory method for assessing the nitrogen-supplying power of soils.

2. *Value and Limitations of the Incubation Method*

The earlier work on nitrification tests has been summarized and discussed by Brown (1916), Fraps (1920, 1921), and Waksman (1923b, 1932). Being certainly the quickest, cheapest, and most convenient method, the incubation technique also has its weak aspects. It should not be forgotten that the incubated soil samples are kept under entirely artificial conditions. The results of such experiments are in no way comparable with the mineralization process under field conditions. In most cases the investigators tried to approach as close as possible to

conditions ideal for the mineralization of organic substances in the samples. Such incubation experiments provide information about the *potential* mineralization power of the soils, whereas under field conditions the *real* mineralization capacity prevails. How significant the difference between field and laboratory conditions is, can be illustrated by the data about the percentage of the N_t mineralized within some weeks in incubated samples. The earlier investigators especially reported sometimes surprisingly high percentages; Lipman *et al.* (1916), up to 25 per cent, Fraps (1920) 7 to 10 per cent, Gainey *et al.* (1937) 8 to 11 per cent for unfertile, and 20 to 25 per cent for fertile, soils. Only Hall (1921) had mineralization percentages of less than 5 per cent. Among the modern data the following figures can be mentioned: Jensen (1940) 0.1 to 0.3 per cent, Jewitt (1945) 2 to 14 per cent, Drouineau and Lefevre (1949a, b) 2 to 8 per cent, Süchting (1949) 5 to 10 per cent, and Acharya and Jain (1954) 4 to 11 per cent. All these figures, even the lowest, are so high that they must be considered to be of an entirely different magnitude from the mineralization under field conditions. Drouineau and Lefevre (1949a, b) even calculated from their lysimeter experiments that the amount of nitrogen mineralized in one month in the laboratory approximately agrees with the quantity washed out in a whole year on the field. Still it is not advisable intentionally to make the incubation conditions less favorable for mineralization, because only by creating optimal conditions can the method be more or less standardized, which is certainly necessary to obtain comparable results. So it must be considered worthless to try to imitate natural conditions in incubation experiments, and we will have to accept mineralization experiments in the laboratory as providing us with an artificial magnitude which has great value but which must be interpreted with care. The most difficult part therefore will not be the carrying out of the incubation experiments but the interpretation of the results obtained for advising the farmers. Therefore it will be necessary to find the relation between the mineralization of nitrogen in laboratory experiments and the nitrogen requirements of the crops. Some characteristics of the incubation methods must be mentioned in connection herewith, to make it clear that it must be considered hopeless ever to attain a general expression for a correct interpretation of incubation results for all types of soils and for all conditions. The only achievement that seems to be possible is to derive, by an elaborate empirical comparison, such relations separately for each soil type.

1. In uncultivated virgin soils and in soils with a poor structure the rate of mineralization, as measured in incubation experiments, is stimulated to a level that is much further above the natural rate of min-

eralization under field conditions than in adequately drained and cultivated arable soils. As a result it can happen that in samples of uncultivated acid, forest, or heath soils more nitrogen becomes liberated than in samples of productive cultivated soils, whereas under field conditions just the reverse situation prevails. Striking examples have been reported by Jolivet and Helias (1953b), by Bel *et al.* (1951), and by Duchaufour (1951). This observation must be ascribed to the fact that the organic N in the aerated arable land already had been partially mineralized *in situ*, whereas in the forest and heath soils its decomposition had been hampered because of unfavorable conditions. The above statement can be formulated in a more general way: the acceleration of the mineralization of C and of N during incubation can vary considerably in different soils, depending on the C:N ratio and on the resistance of the organic compound to mineralization (compare Sections II, 4, and II, 6*a*).

Thompson and Black (1950) and Cornfield (1952) studied the influence of the carbon content of soil on the mineralization of nitrogen in incubation experiments. This relation was not always clear, since in it two factors are counteracting one another: (1) C_t and N_t are generally highly significantly correlated, and therefore the higher the C_t the more N will be mineralized, but (2) high C_t is often also related to a high C:N ratio and therefore can also give low N mineralization. So it depends on the type of humus, on its C:N ratio, and on the influence of the changed conditions of the incubation whether mineral nitrogen accumulation will be correlated positively or negatively with these factors.

One of the consequences of the above-mentioned influence of the type of organic matter in the soil on the rate of mineralization of nitrogen is the impossibility of applying the incubation method to grassland and forest soils. In such soils the high amount of fresh organic material suppresses for a long time any appreciable liberation of nitrogen. Only incubations for very long periods can be applied, and as a result the method becomes too time-consuming. Richardson (1938) experienced this difficulty in studying permanent grassland plots. Even applying very long incubation periods he found surprisingly small differences between the plots, though entirely different treatments had been imposed for many years on these plots, and the appearance of the grass cover was also highly different.

2. The liberation of mineral nitrogen during incubation proved also to be significantly influenced by the conditions which prevailed in the field before sampling: cultivation, cropping, fertilization, and the meterological seasonal factors. They all influence the course of miner-

alization in the samples. In Section II, 1, 2, 3, 4, 8, many examples of such influences of preceding treatment and cropping have been mentioned, and striking data about the influence of the time of sampling have already been presented by: Starkey (1931b), Goring and Clark (1949), Fitts *et al.* (1953), Drouineau and Lefevre (1949a, b), Richardson (1938), Duchaufour (1951), and Kaila (1952b). Starkey (1931b) correctly concluded that determination of the N mineralization capacity of the soil is of no value when done with cropped soils or shortly after the growth of plants, since the surplus of fresh organic matter with a high C:N ratio in such soils prevents normal liberation of nitrogen (Section II, 4). Therefore, the best time for the investigation of the mineralization capacity by means of incubation should be the spring. Only at that time can values corresponding with the N requirement of the crops be obtained. Goring and Clark (1949) performed pot experiments with periodic analyses of the soil for mineral nitrogen. They found that N mineralization was approximately the same in cropped and fallow pots during the first 5 weeks; thereafter the nitrogen accumulation in fallow soils continued as a straight line, whereas it became more and more curved towards the horizontal for cropped soils. After 13 weeks the cropped soils showed scarcely any further nitrogen mineralization. The necessity of confining the performance of incubation experiments to the spring and late winter is not only the result of the formation during the summer of fresh organic substances in crop residues and in the "rhizosphere effect" but is also due to the fact that the preceding winter exerts a "partial sterilization effect" on the soil, as has been discussed in Section II, 8. Drouineau and Lefevre (1949a, b), for instance, found considerable fluctuations in the mineralization capacity of soils sampled for incubation experiments in different seasons. The fastest nitrogen mineralization was obtained in samples collected between December and April. During the development of the crops in the following months the mineralization capacity decreased significantly and remained at a rather constant low level, as recently has been confirmed by Fitts (1953) and Fitts *et al.* (1953). Between May and September, these differences were less than 10 p.p.m.

The requirement to use in incubation experiments only samples taken during the late winter and spring is, of course, very inconvenient, piling up the work in this season. Many investigators therefore tried to preserve samples collected in those months in an air-dry condition (Jeffries, 1932; Black *et al.*, 1947; Pritchett *et al.*, 1948; Drouineau and Lefevre, 1949a, b; Allison and Sterling, 1949; Martin, 1949; Cornfield, 1952, 1953; Kaila *et al.*, 1953; and some earlier investigators). In most cases, however, the desiccation of the samples resulted in a pronounced

"partial sterilization effect," enhancing the rate of mineralization. This procedure consequently can be applied only when all samples are dried before using them for incubation experiments, otherwise the results are not comparable. This disturbing effect of drying the samples was not observed when only the nitrification of ammonia, rather than the entire mineralization, was studied, as has been reported by Martin (1949), applying the perfusion technique of Lees and Quastel.

3. In our variable climate the mineralization capacity of soils is influenced not only by the treatment of the soil prior to sampling and by seasonal factors but also by differences in climatic conditions between consecutive years. Pritchett *et al.* (1948), for instance, observed a marked difference between the results obtained in 1944 and 1947, under otherwise completely comparable conditions. According to the regression equations the response of oats to nitrogen fertilization was nil on soils producing 86 p.p.m. or more nitrogen during incubation in 1944, whereas in 1947 this point was reached with 50 p.p.m. of mineralizable nitrogen. Van Schreven (unpublished) recently confirmed this experience for a series of very uniform soils in the newly reclaimed polder of the Zuiderzee.

4. The last shortcoming of the incubation technique that must be mentioned here is the irregularity of the curves of accumulation of mineral nitrogen during incubation, observed by some investigators. Whereas most workers received nicely straight or regularly curved smooth lines when plotting the mineralized nitrogen against time, some others reported an irregular increase of the mineral nitrogen with sharp fluctuations. Such cases have been reported by Millar *et al.* (1936) and by Gerretsen (1942). Gerretsen concluded that the nitrogen metabolism in incubated soil samples depends entirely on the interference of ammonification and the reverse process of the assimilation of mineralized nitrogen by microbes, both processes having a very dynamic character, with sharp fluctuations even under constant conditions.

To summarize all the above-mentioned difficulties and shortcomings of the incubation technique, it must be formulated that reliable results, sufficiently correlated with the nitrogen requirement of field crops, can be expected only when the incubation technique is restricted to one soil type, one climatic zone, and one farming system and when all samples are collected within one season, preferably during the early spring. For each set of conditions the interpretation of the results obtained must be developed separately. Besides these limitations of the incubation method the results and their interpretation certainly will vary from one year to another, owing to uncontrollable and often unpredictable variations of the weather conditions. So the accuracy of the incubation

method should never be overestimated, and consequently the determination of the nitrogen requirement of soil presumably never will reach the same accuracy as the determination of P and K requirements. Finally it must be accepted that the incubation method in practice is not applicable to grassland and forest soils. In view of these limitations it must be considered surprising how often investigators using the incubation method have reported satisfactory or even good correlations between the results obtained and the response of field crops to nitrogen dressings. Such good correlations have been found not only as a result of long-term, carefully studied experiments, taking into account the above listed limitations, but sometimes also in superficial or incidental experiments. Some authors did not even realize how wrong the results of incubation experiments can be, and how dangerous it is to translate them into fertilization advice without all necessary precautions. In most cases the satisfactory correlation presumably could be attained because these investigations were performed with different plots of one experimental field and consequently on one soil type. The relation between the power of mineralization, determined by incubation experiments, and crop production has been mentioned by many workers, for example, by: Kellerman and Allen (1911); Stevens and Withers (1912); Fraps (1912, 1916, 1920, 1921); Brown (1912, 1916); Lipman (1914); Lipman *et al.* (1916); Gainey (1917); Burgess (1918); Waksman (1923b); Gowda (1924); Sievers and Holtz (1926); Nemec (1926); Jeffries (1932); Fraps and Sterges (1947); White *et al.* (1949); Allison and Sterling (1949); Fitts (1953); and Fitts *et al.* (1953). Generally a fair correlation was found between crop and nitrate production, but many individual soils showed wide variations. In recent years good agreements have been reported by the following investigators. Varallyay (1935, 1937), working with Hungarian wheat soils and applying surprisingly short incubation periods of only 14 to 20 days at the temperature of 35° C., achieved good correlations, enabling him to develop recommendations as to the nitrogen fertilization. Richardson (1938) found sufficient correlations even for grassland soils, applying, however, very long incubation times. Black *et al.* (1947) and Pritchett *et al.* (1948) also reported significant correlations between incubation experiment results and the nitrogen needs of different field crops. Exceptionally good correlations have been reported by Allison and Sterling (1949), working with a very homogeneous soil. The same explanation holds true for the work of White *et al.* (1949), who also obtained correlations beyond the 1 per cent level of reliability. Some valuable material was collected in the years 1948 to 1954 by van Schreven in the ploders of the reclaimed Zuiderzee (not yet published). Confining the

calculation of the correlation coefficients to soils of one type, he was able to derive from his incubation experiments rather accurate and correct advice for the application of nitrogen fertilizers. Rubins and Bear (1942), studying the mineralization of different organic substances added to soil, obtained a satisfactory correlation between nitrogen liberation in incubation experiments and responses of different crops, cultivated in pot experiments, to the application of such organic additives.

Wholly negative results have been reported in only a few cases. Jeffries, in his earlier work (1932), achieved only fair correlation between nitrogen mineralization in incubation experiments and crop demands, using soils from limed and fertilized (P, K) plots. He explained this as a result of other factors limiting the effect of nitrogen in the unfertilized plots. A complete failure to find a relationship between nitrogen mineralization in incubation experiments and the productivity of the soil under field conditions has been reported by Jolivet and Helias (1953a, b).

3. *Various Procedures for Carrying Out the Incubation Method*

In the simplest type of incubation experiment the analysis for mineral nitrogen is performed only twice: at the beginning and at the end of the incubation period. The difference between these two determinations divided by the length of the incubation period gives the average rate of mineralization during the experiment. This procedure certainly is work-saving, but it depends entirely on the assumption that the rate of mineralization remains more or less constant throughout the whole incubation. This assumption, however, has proved in many cases not to be correct. Apart from the well-known depression of nitrogen mineralization during the first weeks of incubation in all soils rich in undecomposed organic matter with a high C:N ratio, the rate of mineralization normal in soils has been found by many investigators not to be maintained at the same level during a prolonged incubation period. Therefore other investigators did not rely upon the determination of mineralized nitrogen only at the end of the incubation, but repeated this analysis at shorter or longer intervals during the incubation period. In recent years such careful investigations have been reported by Allison and Sterling (1949), White *et al.* (1949), Harmsen and Lindenbergh (1949), and Acharya and Jain (1954); similar, as yet unpublished, work has been carried out by van Schreven recently.

By following this procedure of repeated analyses during incubation, it is possible to plot the results in graphs, thereby illustrating the course of mineralization. In all such investigations the rate of nitrogen mineralization proved to decrease with time. The curves in the graphs con-

sequently are more or less bent towards the horizontal. Various reasons have been proposed to explain this gradual decrease in mineralization. Allison and Sterling (1949) tended to ascribe it primarily to the increasing acidity with the rise of nitric acid content during incubation. They found support for this opinion in the observation that poor soils, with an initially low pH, demonstrated this phenomenon in a more pronounced way than richer soils with higher pH levels, notwithstanding the fact that the latter were richer in nitrogen and accumulated nitrates more rapidly. The poor soils apparently could not neutralize the nitric acid formed. Other investigators, such as, for instance, Harmsen and Lindenbergh (1949), expected that an increasing concentration of mineral nitrogen would stimulate the reverse processes of synthesis of organic matter by the microbes, and thereby would counteract the mineralization. They, therefore, presumed that in incubation experiments in the long run an equilibrium between mineralization and rebinding of the nitrogen will always be obtained. The mineral nitrogen content should then more or less indefinitely fluctuate around the equilibrium level without further rise. However, this equilibrium state was reached only after a very long incubation. In the work of Allison and Sterling (1949) this point was reached only after about 3 months, and a similar figure has also been reported by Harmsen and Lindenbergh (1949) and by van Schreven in work as yet unpublished. Consequently the rate of mineralization during the first six or eight weeks, and in some cases even during a longer period, proved to be rather constant, and to be represented by nearly straight lines in the graphs. So the gradual decline of mineralization during prolonged incubation proved not to have adverse effect in practice upon the performance of incubation experiments, since the incubation time seldom has to be more than six weeks.

In practically all cases where a gradual retardation of the mineralization has been observed, this slowing down and ultimate cessation of nitrification could be overcome by leaching the samples with water and allowing the soil to incubate again. Even some earlier investigators reported this effect of leaching (Fraps, 1920; Lyon and Bizzell, 1913a, b; Lyon *et al.*, 1920; Jensen, 1940). Especially Fraps observed a very marked effect when leaching his soils from the arid region in Texas. In recent years the periodic leaching of incubated samples has been applied by Jensen (1950a), van Schreven (unpublished), Stanford and Hanway (1953), and Acharya and Jain (1954), always with the result that the mineralization was restored. Totaling up the amounts of mineral nitrogen found in the subsequent leachings, a much higher total mineralization was obtained than in uninterrupted incubation. More-

over, the process of mineralization now seemed to go on more or less indefinitely. This effect of leaching the samples agreed very well with the explanation of the slowing down of the mineralization based on the assumption that the increasing acidity or the enhanced synthesis of microbial protoplasm was responsible for the suppressed accumulation of mineral nitrogen. The problem consequently seemed to be sufficiently demonstrated and explained. Yet Acharya and Jain (1954) recently proposed another explanation for this phenomenon. They also observed the gradual decrease of the speed of mineralization during incubation and the attainment of a constant maximum mineral nitrogen level in about four to six months. They also found that they could reactivate the mineralization by leaching their soils. But they found further that the accumulation of mineral nitrogen could not be the retarding factor, since the addition of potassium nitrate to the samples did not interfere with the course of nitrification. Moreover, pH measurements revealed no perceptible fall in pH during nitrification. Therefore they supposed that water-soluble toxins or other growth-inhibiting substances may be formed during incubation which ultimately suppress the mineralization.

Expecting a depressing influence of high contents of mineral nitrogen on the rate of mineralization, Harmsen and Lindenbergh (1949) tried to remove all mineral nitrogen from their samples before incubation. All mineral nitrogen was extracted from the soil samples by cultivating spinach (*Spinacea oleracea* L.) upon it, and not by percolating with water, to prevent an unfavorable change in the structure of the soil. This pretreatment, however, makes the method expensive and time-consuming, since it takes five to six weeks before the plants have exhausted all available nitrogen, and show symptoms of N deficiency. In later (not yet published) experiments of Harmsen and van Schreven, in agreement with the opinion of Acharya and Jain (1954), no adverse effect of high initial contents of mineral nitrogen on the rate of mineralization could be demonstrated. Besides, in recent, also not yet published, experiments of van Schreven, Gerretsen, and Harmsen it was found that after cultivation of spinach in most cases not more, but less, nitrogen was mineralized; this agrees with the results of Goring and Clark (1949), and of Bartholomew and Clark (1950a, b). This must be ascribed to the rhizosphere effect of the spinach (Sections II, 2 and II, 4). In consequence of the recent investigations just mentioned the method developed in 1949 by Harmsen and Lindenbergh is no more in use. In most cases even high initial contents of mineral nitrogen do not measurably interfere with the mineralization.

Stanford and Hanway (1953) also are removing from their samples at the beginning of the incubation all mineral nitrogen by placing the

small samples in filter tubes and leaching them free of nitrate with water. Their purpose, however, is not to prevent the suppression of the mineralization by high initial contents of mineral nitrogen, but only to avoid the necessity for the initial analysis. In serial work it therefore is possible, following their procedure, to determine the mineralization capacity with one analysis, but it also is possible to repeat the leaching of the same sample more than once if the course of mineralization must be studied, since the samples are incubated in the same filter tubes.

Even earlier some investigators mixed their soil samples with pure quartz sand, and in recent years this was done by Black *et al.* (1947), Pritchett *et al.* (1948), Drouineau and Lefevre (1949a, b), Bel *et al.* (1951), Duchaufour (1951), and Jolivet and Helias (1953a, 1953b). The purpose of this procedure is to improve the structure of heavy sticky soils, while if the samples must be percolated, the admixture with sand increases the permeability of the sample. All the above-mentioned investigators were satisfied and considered that the addition of sand certainly served its purpose, but it is more than questionable whether the soils are not thereby changed so entirely that the observed results nc longer correspond with the characteristic properties of the samples. This objection is even more true for the admixture of "vermiculite" as applied by Stanford and Hanway (1953), though thereby not only is the permeability improved but also the maintenance of a constant moisture content is facilitated. Yet Stanford and Hanway reported a good correlation between their incubation results and the nitrogen requirement of field crops.

The use of soil mixed with sand or some other inert granular substance is inevitable in applying the perfusion method of Lees and Quastel. Though this method has been repeatedly used for the study of mineralization of nitrogen, it is not necessary to describe it here, since Lees and Quastel in 1944 and Lees in 1947 gave a complete report of their technique. Lees and Quastel with some of their collaborators (compare Sections II, 6*a* and III, 1) as well as Bould (1948), Martin (1949), and Wright (1953) published results of nitrogen mineralization studies performed with this method. Yet the perfusion procedure must be considered rather unsuitable for this purpose, since the conditions of incubation provided are so artificial and deviate so far from those in the field, that the results obtained are too uncertain. Wright (1953) already arrived at the same conclusion. In most cases, however, this method was not adopted for the determination of the mineralization capacity of natural soils, but for the study of the mineralization of added organic substances or of the nitrification of added ammonia.

In Section IV, 2 the incubation method was criticized on the grounds

that the nitrogen mineralization is determined under too artificial conditions, and it was accepted only because there seems not to exist a better method. The same objection must be expressed therefore even more emphatically against further far-reaching treatments of the samples before incubation. Many investigators even as far back as 1913 (Paterson and Scott, 1913; Gowda, 1924; Brown and Gowda, 1924; Jeffries, 1932; Dean and Smith, 1933; Fraps and Sterges, 1932, 1937, 1939a, 1947; Allison and Sterling, 1949; Yankovitch and Yankovitch, 1954) proposed to fertilize the samples with P and K, to lime, and sometimes even to inoculate them with an infusion of a fertile active soil. This method was particularly advocated in the earlier years by Fraps and Sterges (1939a) and recently by Allison and Sterling (1949). Their main idea is thereby to remove as far as possible the many factors which may be limiting mineralization, or at least to make conditions uniform. It is, however, evident that by adding nutrients, by improving the reaction, and by inoculating this improved medium with a microflora derived from another soil, a significant artificial stimulation of the mineralization of nitrogen can be achieved, just as well as by the improvement of the structure by adding sand or vermiculite. It must therefore be presumed that by all these measures most differences between the soils will be leveled. Even in the worst acid sticky soils, poor in minerals, vigorous mineralization of nitrogen can be initiated, if only these soils contain enough N_t. The method of Allison and Sterling consequently eliminates all other properties of the soils and determines exclusively the availability of nitrogen in the humus under optimal conditions. A similar opinion about this method has already been expressed by Cornfield (1952), comparing incubation of limed and unlimed samples.

In the beginning of Section IV, 2 it was stipulated that the variable factors, i.e., those factors which even under field conditions in each soil can vary considerably, such as temperature, moisture, and aeration, must be regulated in such a way that optimal mineralization conditions are provided, as long as the characteristic properties of the soils studied are not too much altered. This consideration induced most investigators applying incubation methods to keep the soils under optimal aeration conditions. Harmsen and Lindenbergh (1949) also expected the highest rate of mineralization of nitrogen at optimal aeration. They, therefore, intentionally used shallow unglazed earthenware dishes for the incubation. But this presumption proved not to be correct. van Schreven (unpublished) has repeatedly shown that N mineralization in many soils was retarded when they were kept at optimal aeration, as, for instance, when the samples were spread in a thin layer of only a few

centimeters. This was especially true for soils with pH 7.2 to 7.8, incubated for 18 weeks. It often happened that an initial increase of mineral N in such soils was followed by a decrease, sometimes continuing until complete disappearance of all mineral N. This adverse effect of the maintenance of the samples in very thin layers cannot be ascribed to desiccation nor to the influence of irradiation, since the moisture content of the samples was carefully controlled and the samples were kept in a dark incubator. It, consequently, seems to be inadvisable to incubate soil samples with too vigorous aeration. For obtaining comparable results, the aeration must be standardized either by always using the same shape and size of container or by incubating the samples in vertically placed tubes with a very gentle air flow passing at a constant rate through them. Some unpublished experiments by Harmsen showed that soil samples incubated in tubes of 5-cm. diameter had the highest rate of accumulation of mineral N when about 0.2 l. of air was led through each sample per hour. More vigorous aeration retarded the mineralization considerably. Another consequence of this procedure is that if it is desired to determine the mineral N content more than once during the incubation, the thickness of the soil layer may not be decreased, as should be the case if a single sample is used. Several small containers therefore must be used for one sample, removing a whole container for each periodic analysis. It is not yet clear how these observations can be explained. A similar observation has also been reported by Fitts (1953) and by Fitts *et al.* (1953). They incubated their samples in milk bottles and tried to reduce evaporation by closing the bottles with one-hole rubber stoppers. The aeration undoubtedly was reduced hereby. Samples of 25 or 100 g. showed a faster mineralization than very small samples of only 10 g.; apparently because in the latter aeration was still above optimal even in the partly stoppered flasks. However, the size of soil aggregates in their samples had no influence on the mineralization. Black *et al.* (1947) and Pritchett *et al.* (1948) obtained the highest mineralization rates incubating their samples in sealed jars, opened only once a week for aspiration with fresh air.

In the preceding sections the question as to whether the mineral N in soils is practically entirely represented by nitrates or whether ammonia also constitutes an important part of it, has been fully discussed (compare: Sections II, 2; II, 3*a*; II, 3*b*; II, 3*d*; II, 7; II, 8; III, 1; and III, 3). It may be assumed as evident that in most soils during incubation nearly all available N is found as nitrates. For that reason many workers confine themselves to the determination of nitrate accumulation. By doing so, they are avoiding all difficulties of the quantitative determination of ammonia in soil. Nitrate, being a substance practically

not absorbed by the soil, can easily be extracted, and the analysis of it in the extract does not present any special difficulties. Ammonia, on the other hand, is partly absorbed by all soils and sometimes even retained despite drastic extraction procedures. Unfortunately there are soils in which ammonia does not constitute a negligible part of the mineral nitrogen. All soils with too low pH, insufficient aeration, or too much organic matter, as well as partly sterilized soils, usually contain much ammonia, and the mineralization process in such soils often stops at the stage of ammonification without subsequent nitrification. Therefore it was long ago (Bogdanow, 1900; Nemec, 1926; Nemec and Koppová, 1932) recognized that the incubation method should be applicable to all soil types only if the determination of the mineralized nitrogen is not restricted to the analysis of nitrate. In recent years this opinion has again been underlined by Allison and Sterling (1949), Harmsen and Lindenbergh (1949), and Cornfield (1953). Some investigators, therefore, applied separate determination of NO_3-N, NO_2-N, NH_4-N, and sometimes even of organic nitrogen in the extracts, whereas others have tried to simplify the procedure by the adoption of analytical methods, which allow the determination of all forms of soluble nitrogen together. For this purpose either some modification of the Jodlbauer-Kjeldahl method has been used or one of the reductive methods, such as that of Devarda (1893), Arnd (1917), or Cotte and Kahane (1946). The Kjeldahl methods, being by far the most time- and work-consuming, have gradually been abandoned, and in recent studies only the reductive methods with the formation of nascent hydrogen are applied, despite the difficulties met with extracts that may be rich in nitrogen-containing organic substances. In some soils such organic extractable N-compounds may be found in high concentrations in the soil extracts. Especially peat soils and acid sandy soils, rich in humus, provide such extracts. Whereas in more or less neutral or alkaline mineral soils the total extractable nitrogen, even at the end of an incubation period, seldom exceeds 50 or 60 p.p.m., peat soils even under field conditions sometimes show 200 to 300 p.p.m. extractable nitrogen. Yet such peat soils require more nitrogen fertilization than the mineral soils. Apparently these substances are not absorbed by the plants in their nitrogen nutrition. No data seem to be available about the chemical characteristic of these organic extractives, but from the work of Warner and Cannan (1942) it must be concluded that not only amino acids but also some alkali-labile substances are present therein. This water solubility of organic substances can even be enhanced by the extraction of the soil with electrolytes, especially by sodium compounds, as has been observed by van Schreven (unpublished report) and by Schachtschabel

(1954). During distillation of extracts containing such organic substances, part of the latter becomes decomposed and ammonia may be split off. Consequently more ammonia is distilled over than really was present in the soil extract. The higher the alkalinity in the boiling solution, the more ammonia will be split off. Therefore distillation with NaOH, applying the Devarda method, provides much more ammonia than distillation with MgO. Very striking examples of this have already been reported by Ranker (1927), distilling extracts of bacteria, molds, plants, and compost. However, even at the moderate alkalinity of MgO distillation, some organic nitrogen distills over with the genuine ammonia, as has been observed by van Schreven and Harmsen. Shrikhande (1941) had a similar experience working with plant extracts. He therefore recommends keeping the reaction of the extract during distillation at pH 7.4 by means of a phosphate buffer. Hendricks *et al.* (1942) recommends replacement of the distillation by bubbling a gas at room temperature through the solution, thereby transferring the ammonia to the receiver. Neither of the last mentioned methods, however, guarantees complete recovery of ammonia.

Besides the disadvantage of the Devarda method arising from the decomposition of organic substances in the highly alkaline boiling medium, Brabson and Krachmer (1945) claim that too low results sometimes may be obtained as a result of liberation of silicate from the glass of the distillation bottle. Drouineau and Gouny (1947) confirmed this observation and were able to get quicker distillation and higher nitrogen contents if more Devardas alloy was used. They tried to explain this phenomenon by the presumed formation of a film of Al silicate around the Al particles of the Devardas alloy, resulting in reduced reaction of the Al with the alkali.

In addition to the reduction of nitrites and nitrates with nascent hydrogen in the Devarda method, several attempts have been made to accomplish this reduction with $Fe(OH)_2$ and alkali (Zorn, 1882; Baudisch and Mayer, 1920; Miyamoto, 1922), but a complete reduction could be achieved only at the sacrifice of very long distillations (3 to 3½ hours). Only recently Cotte and Kahane (1946) succeeded in improving this method by the introduction of silver sulfate as catalyst. The principle of this reaction may be written as follows:

$$NO_3^- + 8Fe(OH)_2 + 6H_2O \rightarrow 8Fe(OH)_3 + OH^- + NH_3$$

The method of Cotte and Kahane was critically tested by Karsten and Grabé (1948) and recently by van Schreven (unpublished), who found the method to be of the same value and accuracy as the method of Devarda. Moreover, it has the advantage that it is quicker and that no mist

is formed above the boiling liquid whereby alkali could be transported to the receiver. However, the method of Cotte and Kahane, requiring the same high alkalinity as the Devarda method, is not applicable to extracts rich in organic substances.

The methods reducing nitrites and nitrates with metallic iron or alloys in an acid medium (for instance, the method of Ulsch, 1890) are more laborious, since reduction and distillation are not achieved simultaneously. Moreover organic substances are decomposed in this procedure also. The last-mentioned disadvantage of these methods, as well as of the Kjeldahl procedure, can sometimes be avoided by replacing the alkaline distillation by a direct colorimetric determination of the ammonia after digestion, using the Nessler's reagent, as has been proposed by Johnson (1941). However, this colorimetry is not very reliable. It often is interfered with by some of the constitutents of the digestion liquid. Methods whereby reduction and distillation are performed with much lower alkalinity—such as the method of Arnd (1917)—unfortunately also cannot be considered entirely reliable, since it is doubtful whether the reduction of nitrates will always be complete.

Another method for determining inorganic nitrogen fractions in soil and plant extracts was presented by Wolf (1947). Nitrate and nitrite nitrogen are quickly reduced to ammonia at room temperature by the use of a titanous chloride solution. This method has moreover the advantage that the ammonia can be determined photometrically by use of a modified Graves' reagent. However, the accuracy of this method is limited and nitrites are not fully recovered (compare Section II, 7).

In summarizing the above comments about the different methods proposed for the simultaneous determination of all forms of mineral nitrogen, it must be concluded that no one of these methods can be recommended for all soil types. Especially soils containing extractable organic substances should not be assayed by one of these methods. For entirely reliable determinations a separate analysis of the extracts for ammonia, nitrite, and nitrate therefore must be considered inevitable.

In the earlier investigations the determination of nitrate generally was performed by the use of the diphenylamine method, but, being not specific for nitrates, it has later been abandoned. In modern papers the phenoldisulfonic acid method is the one most used (Prince, 1945; Official Methods Agr. Chemists, 1945). This method, however, requires very careful colorimetry. Berge (1941) studied this method extensively, using the photoelectric colorimeter of Evelyn (1936). By taking certain precautions he succeeded in achieving accurate measurements even when the extracts were slightly pigmented or turbid. The phenoldi-

sulfonic acid method recently has repeatedly been used, for example, by Allison and Sterling (1949), Cornfield (1952, 1953), and Kaila *et al.* (1953). Another good colorimetric method was proposed by Blom and Treschow (1929), who used orthophenol (1,3,4-xylenol) for the transformation of HNO_3 into nitro-xylenol. This method has not been much used, but it certainly is worth restudy, since it is in some aspects superior to the phenoldisulfonic acid method, being interfered with neither by soluble organic substances in the extracts (H. Barnes, 1950; Balks and Reckers, 1954), nor by NaCl, which in the phenoldisulfonic acid method has to be removed by $AgSO_4$.

Nitrate and nitrite determinations sometimes give too low results, no matter what the method of analysis may be, especially when the extracts are concentrated by evaporation, maintaining an acid reaction (compare Section III, 4*b*).

The determination of nitrites, when performed separately, practically always has been done by the use of Griess' reagent.

Ammonia determination mostly has been performed either by distillation with MgO or by a direct colorimetry with Nessler's reagent in the original extracts (Cornfield, 1952). Considering the simultaneous determination of all forms of mineral nitrogen together it has already been mentioned that the MgO distillation of liquids containing organic substances sometimes gives faulty results. The methods of Shrikhande (1941) and of Hendricks *et al.* (1942), who tried to avoid this difficulty, can of course also be used for the direct separate determination of ammonia in the extracts. When ammonia is determined by any distillation method its content in the receiver can be estimated either titrimetrically or colorimetrically with Nessler's reagent, as has been proposed by Nemec and Koppová (1932).

Finally, it must be mentioned that a separate determination of ammonia and nitrate also can be accomplished by first distilling off the ammonia with MgO, and then using the same extract or another part of the original extract for the reduction of nitrates by the Devarda method (Jensen, 1952).

It has already been mentioned that, whereas nitrate is not absorbed or retained in any way in the soil, ammonia, on the contrary, is more or less absorbed in all soils. Nitrates, therefore, are entirely and immediately available for plants and microbes, whereas part of the absorbed ammonia is so strongly bound that neither microbes nor plant roots are able to utilize it. Unfortunately all grades of availability from free, soluble ammonia ions until strongly bound, scarcely extractable forms are found in most soils. It is therefore difficult in the evaluation of ammonia in soil to assess that part of it which can be utilized by plants.

Ammonia is absorbed by humus, but primarily by the clay minerals, and it even may be bound by the crystal lattice of the latter. The ammonia absorbed on the surface of the crystals may be removed by an excess of another cation. The liberation of the ammonia from the inner layers, however, is much more difficult, and the amount which may be displaced depends on the cations which are used for the exchange. In this connection it may be mentioned that Barshad (1948) observed a better exchange of ammonia from crystal lattices of clay minerals by Na^+ than by K^+. Van Schreven and Harmsen (unpublished report) confirmed this observation. It is more than questionable whether plant roots are capable of taking up the ammonia from the crystal lattices of the clay minerals. According to Allison *et al.* (1951) and Bower (1951) the ammonium which is not removed by leaching the soil with normal KCl solution is only slightly available to nitrifying bacteria, and according to Bower (1951) and Allison *et al.* (1953b) also to higher plants, and since it may be considered as proved that percolation of soil with dilute solutions of electrolytes (KCl or NaCl) removes only the ammonia that is loosely absorbed on the surface of soil particles, it seems that such an extraction more or less corresponds with the ability of the plants. However, this question has not been sufficiently studied. Compare in this connection the studies of Jenny and Overstreet (1939) and Jenny *et al.* (1939). As long as more information about the availability of the different fractions of ammonia for the plant is lacking, it seems justifiable to use dilute solutions of electrolytes for the extraction of the soil samples, when the determination of NH_4-N is required. But this extraction must be strictly standardized. Among the first investigators emphasizing this extraction may be mentioned MacLean and Robinson (1924). In recent years practically all investigators applied one or another modification of such an extraction. Nemec and Koppová (1932) used 200 ml. 0.5 *N* NaCl solution for shaking 100 g. of air-dry soil; Varallyay (1935, 1937) shook 15 g. of soil with 200 ml. 1 per cent KCl solution; Cornfield (1952, 1953) applied 0.5 *N* NaCl in the proportion of 1 soil to 2 solution; Kaila *et al.* (1953) applied a 10 per cent solution of KCl, shaking 5 g. air-dry soil with 100 ml.; and Drouineau and Lefevre (1949a, b) used *N* $CaCl_2$. Cornfield and Kaila both percolated the samples with a certain amount of the same solution after filtration to obtain more complete extraction. Van Schreven (unpublished) showed recently that such percolation of the filtered samples added appreciable amounts of ammonia to the extract. The longer this percolation was continued, the more ammonia could be leached out of the sample, though of course with diminishing returns. Ammonia, apparently, can never be extracted completely with dilute electrolytes,

since this extraction is based upon equilibrium reactions; the preparation of the soil extracts consequently always will be an arbitrary procedure requiring strict standardization if comparable results are required.

Olsen (1929a, b) proposed a much stronger extraction with the purpose of assessing thereby all the ammonia. He also used dilute solutions of KCl or NaCl but acidified the suspensions with HCl to pH 1. Black *et al.* (1947), Pritchett *et al.* (1948), and Jensen (1952) applied the same method. Of course the results obtained with this modification are not comparable with those obtained with extraction at a neutral reaction.

The capacity of soils to mineralize nitrogenous organic substances can be studied by incubation either without but also with an added nitrogen source. Some investigators considered that by the latter procedure the difference in the potential mineralization capacity of soils could better be demonstrated. It is of course not possible to compare these results with those obtained without additives. This method consequently serves an entirely different purpose. It has many times been applied, often without sufficient realization of the consequences of the artificial addition of nitrogenous organic matter. Sometimes this method was used in parallel with the incubation without additives, and even with other procedures with the purpose to obtain as complete data as possible (Waksman, 1923a).

It is not necessary in this Section to review the papers in which this method has been mentioned, since as far as procedure is concerned the operations in no way deviate from the incubation methods without addition of organic substances. Especially the capacity of soils to oxidize ammonia—true nitrification—has often been studied with this modification, by adding $(NH_4)_2SO_4$ to the samples. Either one of the modifications of the original incubation method or the perfusion method of Lees has been used. An exceptional and rather artificial method was used by Bharucha and Sheriar (1952) for the estimation of the nitrification of ammonia. They added $(NH_4)_2SO_4$ and $CaCO_3$ to the Omeliansky (1899) medium and inoculated it with a certain amount of soil. The rate of NO_3 formation was used as an indication of the nitrifying capacity of the soil.

4. The "Indirect" Incubation Method

The determination of the rate of nitrogen mineralization in soil can be accomplished not only by the direct measurement of the increase of the mineral nitrogen content during incubation but also by measurement of the CO_2 evolved by the sample during incubation with an

excess of a carbohydrate. When such a nitrogen-free, easily mineralizable organic substance in excess is mixed with the soil, and if all other growth factors (P, K, trace elements, etc.) are amply provided, the available nitrogen will become the limiting factor for the decomposition of the added carbohydrate. Consequently the rate of this decomposition may be considered as a measure of the nitrogen mineralization. Of course no mineralized nitrogen will accumulate under these conditions in the sample, and even the available nitrogen present in the sample at the beginning will be consumed within some days by the rapid development of microbes, attacking the added substance. Only thereafter can the determination be started. As a nitrogen-immobilizing substance for this procedure finely divided cellulose has proved to be very convenient, it is sufficiently decomposable to prevent any accumulation of mineral nitrogen, even in very rich soils and compost, and yet not so quickly broken down as soluble sugars. The rate of attack on the cellulose can readily be determined by the measurement of the CO_2 evolved.

The significance of the balance between nitrogen mineralization and cellulose decomposition in the soil was long ago understood. According to Waksman and Heukelekian (1924), Christensen was the first to suggest that the power of the soil to decompose cellulose may serve as an index of fertility. Holben (1932) also observed a close correlation of the cellulose decomposing power of soil with crop production, and in recent times White *et al.* (1949) fully confirmed that observation. They also observed a significant correlation between cellulose decomposition and nitrifying capacity.

To the best knowledge of the writers, Bould (1948) was the first to use the indirect incubation method with addition of excess cellulose in studying nitrogen mineralization not in soil but in compost. Recently Gerretsen (unpublished) applied this method to both soils and compost. The number of investigations using the indirect incubation method is still so small that it is premature to judge its reliability and correlation with crop yields. But the advantages of the indirect incubation method are substantial: (1) the samples do not have to be extracted and all determinations of mineralized nitrogen are avoided; (2) the presence of excess of cellulose during the whole incubation suppresses any accumulation of mineral nitrogen, with the result that no unfavorably high concentrations of mineral nitrogen compounds can ever interfere with further mineralization of nitrogen; an optimal rate of mineralization therefore can be presumed.

However, the conditions prevailing in soil with such an amount of cellulose can by no means be considered normal or typical for soil under

field conditions and certainly not for the period at the beginning of the growth season in spring, while just at that time the rate of nitrogen mineralization is an indication of the availability of nitrogen for the growing crop.

The perfusion method of Lees can also be performed as a direct or indirect incubation, when estimating the CO_2 released from a known weight of soil, with and without admixture of excess cellulose (Lees, 1949; Lees and Porteous, 1950a, b).

5. *The Incubation Method Applied to Organic Fertilizers*

In addition to soil the incubation method can also be applied to many other substances, for the purpose of studying the rate of mineralization of nitrogen in them. From the agricultural point of view only farm manure, compost, and green manure are important. These substances can be added to soil, whereby the decomposition of their content of organic nitrogen proceeds under conditions more or less comparable with those in the field after manuring, but they can also be incubated alone or when mixed with sand or another inert substrate. Here only the first of these possibilities will be discussed, being by far the most important in soil practice.

Many incubation experiments have been carried out with mixtures of soil and organic material. In addition to the earlier investigations the following papers can be mentioned here: Scheibe (1929), Barthel and Bengtsson in a long series of publications (from 1917 to 1940), Jensen (1931, 1932, 1952), Rubins and Bear (1942), and Kaila and Kivinen (1952) studied farm manure (compare Section II, 6*b*); Bould (1948) and Gerretsen (unpublished) used urban compost (compare Section II, 6*b*); Crowther and Mirchandani (1931), Daji (1934), Miller *et al.* (1936), Kalnins (1939), Bjälfve (1952), Kaila and Kivinen (1952), Barnes (1953), and Crowther and Brenchley (1934) added plant residues or green manure to the soils (compare Section II, 6*d*); and Owen and Winsor (1950a, b), Owen *et al.* (1950a, b), and Rubins and Bear (1942) applied this method to many different substances such as Peru guano, bone meal, dried blood, horn and hoof meal, fish and meat meal, and pure amino acids (compare Section II, 6*c*).

It is not necessary in this section on methods to give a complete review of all the above-mentioned investigations, since the procedure fundamentally is the same as when soil alone is used, and the results obtained have already been referred to in the preceding Sections. Only some general aspects of the incubation method with organic additives must be mentioned. It is a general observation that whereas in untreated soils the course of mineralization of nitrogen is only slightly influenced

by sampling the soil and by filling the samples into the incubation containers, the admixture of fresh organic substances upsets the whole metabolism in the soil in such a way that the first period of incubation does not provide reliable results. Pure soil generally gives smooth mineralization curves, rising from the very first day of incubation, without appreciable irregularities. Soils with fresh organic matter, on the contrary, in most cases show a distinct lag period, sometimes even with a temporary consumption of all initially available mineral nitrogen. The most remarkable phenomenon is that even substances with rather low C:N ratios can retard the mineralization in the beginning, if they are constituted of particles with different C:N ratios. Only homogeneous substances with sufficiently narrow C:N ratios sometimes do not show this phenomenon. It seems consequently that the constituents with the widest C:N ratio are more quickly attacked by the microbes providing for immobilization of the available nitrogen during the first days as if they were added alone, while the particles with a narrower C:N ratio reverse this process in the later stages of the incubation. Crowther and Mirchandani (1931) already made this observation. More nitrogen was liberated in their experiments from substances with a moderate C:N ratio than from mixtures of two substances, one with a higher and one with a lower ratio giving a mixture with the same ratio.

The phenomenon of temporary immobilization of available nitrogen has been reported more than once in older publications. In 1931 Jensen observed that the liberation of manure nitrogen only became significant at the time when the microbial numbers were again decreasing after a period of explosive multiplication during the first part of the incubation. In his later work (1952), he confirmed his earlier observations and showed that the lag period with farm manure addition could be as long as 30 to 35 days, coinciding with a maximum development of microorganisms. The mineralization of nitrogen attained its optimal rate not earlier than about 60 to 70 days after the beginning of the incubation. In 1934 Daji, adding about 5 per cent by weight of different plant material to his soils, made a similar observation. All water-soluble N disappeared within the first few days, but soon the mineralization of nitrogen was resumed initially with the formation of much ammonia (up to 500 p.p.m.), that some days later became transformed to nitrate. Kalnins (1939) also observed a marked retardation of the mineralization of nitrogen from lupines incorporated into soil samples. When mineralization later developed and became apparent by accumulation of ammonia and nitrites, just as in the work of Daji, there was a shift of the reaction towards the alkaline side. Some 14 days later, however, nitrification became active, ammonia and nitrites disappeared nearly

entirely, and the pH dropped again. The full rate of mineralization in his experiments was reached only after some 20 days. Very slow mineralization of the N in various substances (fresh and fermented wheat straw, farm manure, green manure, sphagnum peat, and lowmoor peat) and a rather long lag period have recently been reported by Kaila and Kivinen (1952). All these additions caused a depression in the liberation of nitrogen for at least 45 days, and fresh straw and straw compost suppressed all mineralization for nearly a full year. Similar long periods of nitrogen immobilization, have also been reported by Bjälfve (1952, 1953) for soil samples incubated with chopped and ground straw (compare Sections II, 6*a* and II, 6*d*).

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The Place of Microbiology in Soil Science

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CONTENTS

I. Introduction

Soil science is an earth science with roots into geology; yet it is also a biological science because it deals with the formation and characteristics of soils developed in part as a result of biological events, and especially because in its applications it is vitally concerned with the growth of vegetation. But essentially and inherently soil science is a microbiological science too, because in the multifarious processes involved in soil genesis, nutrient release, physical structure, organic matter transformation, to name only a few areas, microorganisms are involved directly. If soil science is indeed a microbiological science, then microbiology should be all-pervading in soil science, without which it would be incomplete and indeed largely inexplicable.

The current literature of soil science, when critically examined in this respect, is not found to provide support for the view that microbiology is all-pervading. It is infrequently the case that there is any reference to microorganisms or microbial processes in most papers reporting soil researches. There is a small percentage of papers dealing directly with soil microorganisms in these same journals, but the percentage of these seems to be less now than 25 years ago. This is not because this material is being published elsewhere. If the general microbiological literature is scrutinized, there can be found few papers that relate microorganisms to soils or plants. Some will be found describing physiological studies on organisms originally isolated from soil, and in some circles these studies may be called soil microbiology.

It is accordingly necessary to make the distinction that although almost all soil problems have microbiological aspects, not all microbiology, so-called, has direct and obvious relationships with soil science. There is a kind of soil microbiology, which is perhaps really a subfield of general microbiology or microbial physiology, in which the prime object of study is some organism with interesting or unique characteristics, isolated originally from soil. In the soil it may be a wholly unimportant member of the vast community of soil organisms, or it may be a prima donna, readily picked out from the crowd. What this organism does may seem to bear not at all on the problems of the soil scientist. The researches are usually not even intended to provide an answer as to whether the organism has any role affecting plant growth or soil processes. The information may, however, add to the general store of microbiological knowledge into which the soil microbiologist proper may dip.

The point emphasized here is that the study of organisms isolated from soil is not necessarily to be regarded as a subfield of soil science. It is perhaps for this reason that some have maintained that soil microbiology is an independent science—a viewpoint which many find unacceptable, because no area of science is independent, least of all a biological science.

In attempting to re-evaluate the place of microbiology in soil science one might start with the observation, made earlier, that little of the published work in soils reflects the basically microbiological nature of many soil processes, and inquire how such a situation could arise. It could have several causes. There might be among soil scientists in general a lack of appreciation or understanding of the roles played by microorganisms in transformations in the soil which affect fertility. Alternatively, there might be among soil microbiologists a lack of realism and a reluctance to subordinate their primary microbiological interests to the search for solutions to problems of plant nutrition and soil management. The documentation of these charges—lack of appreciation on the one hand, or lack of helpfulness on the other—would be something less than convincing. Both may be contributory up to a point, but is it not possible that the situation arises mainly because of the unique and baffling microbiological system that is involved? The systems with which microbiologists have had real success in control are those in which some clearly determinable end product results from the activity of organisms. There is no parallel to this in soil; no specific organism directly releases plant nutrients, no specific organism determines whether or not a soil is fertile. The plant is an interloper in the soil microbiological world—admittedly an interloper that is not without

influence—but one that is dependent on the by-products and side reactions of the soil microflora.

II. The Study of the Microbial Population of Soils

There have been changing concepts of the soil population and the procedures that should be followed in its study. It should be remembered that the soil chemists had identified the major plant nutrients before the existence of an active microbial population in the soil was recognized. Next the nitrification process, first in sewage filters and later in soil, was recognized as being microbiological. At this stage, however, bacteriologists were primarily interested in the identification of pathogenic organisms and their recovery from the soil, in connection with public health problems. The device of the enrichment culture, widely employed by Beijerinck and Winogradsky, marked a great advance. By addition to soil of a compound of interest followed by inoculation into a selective medium containing the same compound, organisms were isolated having specialist properties. In this way many important soil organisms were isolated and described, and the microbiological basis of a number of important chemical transformations was established. Nitrogen fixation, cellulose decomposition, ammonification, ammonia oxidation, nitrate reduction, sulfur oxidation, and so forth were all recognized. The simple concept of cause and effect stemming from the consideration of disease-producing organisms, began to dominate the thinking of those concerned with soil bacteriology. Organisms had to be classified as beneficial or harmful with respect to the growth of plants.

With the recognition that many of the activities of organisms in the soil would be reflected in the supply of nitrogen to plants, attempts were made to express the fertility of soils in terms of its ability to carry out particular transformations, such as, for example, ammonification, this being assessed by the rate of liberation of ammonia from a peptone solution inoculated with the particular soil sample. It was soon apparent that this was not particularly helpful because all that was demonstrated was whether or not the soil contained sufficient organisms capable of carrying out the selected transformation so that an enrichment culture resulted.

In the next phase the test substance was added to the soil itself, and again the rate of change was ascertained after incubation under optimum conditions. A great deal of effort went into this type of study; yet the correlation with crop yields was so tenuous that such procedures were finally abandoned. This was frustrating to the microbiologist, who was being pressed to explain fertility differences, at least in part, by

the microbial make-up of the soil, and who was unable to achieve that measure of control that had proved so spectacular and effective in the field of disease and in the fermentation industries. It should be pointed out that the procedures that were tried were based on the assumption that the soil population consisted of a relatively simple collection of bacterial species each with specialist roles, acting more or less independently, and that the summation of their activities would provide an expression of the potentialities of the soil.

The next phase and one that lasted about 20 years resulted in a considerable broadening of the understanding of what constitutes the soil population. Fungi, algae, protozoa, nematodes, and actinomycetes were all recognized as being normal soil inhabitants in varying degrees of abundance, and many census-like studies were carried out in which attempts were made to count representatives of each group. All were considered to be capable of participating in some of the transformations of interest, though the specialist bacteria still seemed to occupy the center of the stage. Direct interactions were considered as likely; some protozoa, for example, were pictured as being dependent for food on bacterial cells. Once again, however, there was disillusionment when the attempt was made to correlate the results of such counts with known properties of the soil. That these counts had some meaning was apparent from profile studies in which great differences were obvious between adjacent horizons. Similarly, in some management trials the effects of different rotations showed up clearly in population differences. Yet the proper interpretation of numbers remained in grave doubt; it was not clear whether a high count of a particular group was necessarily more desirable than a modest count. Moreover, grave sampling difficulties are encountered if real statistical significance is sought; the recognition of short-period fluctuations in numbers of bacteria was particularly difficult to overlook.

In the next phase many workers adopted the philosophy that the population of the soil is so complex that to endeavor to separate out from it individual organisms to which specialized functions must be ascribed is largely unprofitable. They considered that to ascertain what the population as a whole can accomplish is more important than to attempt to determine what individual does what. Their attitude is summed up in the quotation from Cutler " . . . a population has been developed by evolution which is on the whole so unspecialized that almost any substance that finds its way into the soil, whether naturally, or as a result of agricultural practice, will eventually be incorporated in the general soil economy."

Most soil organisms possess a wide range of enzymes or have the

capability of developing adaptive systems when presented with an unusual, alien, or exotic energy source. The versatility of a population is therefore astonishing, all the more so perhaps because soil in a beneficent environment for inactive forms which maintain viability through long periods of inactivity. The net effect is that a soil can be treated experimentally as if it were a simple organism or a tissue, the capability of which to utilize any compound or group or compounds can be determined. This approach has been widely used in biochemical studies in recent years. A modification involving percolation or perfusion with a solution of the test material, developed by Lees and Quastel, combines this principle with the elective culture principle of Winogradsky. Continued presentation of the test compound results ultimately in the mass development and domination of those organisms which can most efficiently utilize it. Information about possible routes of breakdown may be obtained by supplying suspected intermediates or inhibitors.

It should be said that this biochemical approach has not been too acceptable to some microbiologists trained along classical lines of pure cultural bacteriology, and these have been responsible for a dichotomous development. Some of these men have concentrated their attention on the immediate vicinity of plant roots, which they designate as the rhizosphere. They have demonstrated that in this zone and as a direct result of the presence of living roots there develops a population both qualitatively and quantitatively different from that present in the uncropped soil or in the soil at a distance from the roots. They have shown that the types and numbers present are influenced by the species of plant, and that the rhizosphere population is not just a more numerous and more active version of the soil population at large. They have found that the bacteria of the rhizosphere possess more complex nutritive requirements than do many of those in the same soil uncropped, and indeed have attempted to use this in characterizing the rhizosphere flora and in determining whether changes can be effected therein by management practices.

The development of the rhizosphere population is, of course, an enrichment phenomenon; the forms that arise and become numerous are stimulated to do so by the nutritional circumstances in the vicinity of the roots. The rhizosphere flora presumably contains no organisms that are not present in the soil at large. However, the question does arise as to which soil population is the one of significance with respect to the nutrition and welfare of the plant. Should there be primary interest in the microflora of the zone in which the roots are present, which in great measure results from the presence of the roots, or should attention be confined to the microflora of the zone unaffected by plant roots? If a

cropped soil is sampled, does the information obtained relate to a nonexistent population that is just a mixture of the floras of the two zones? If so, how should any data obtained thereon be interpreted? It is not at all unlikely that the presence of a crop may have a greater influence on the nature of the soil population active in the vicinity of the roots, than differences between the populations of two soils may have upon the growth of a crop.

Each of these various phases of study or approaches has ended in a measure of frustration to the investigator because he has found himself unable to disentangle the mass of information which he obtained. The nonmicrobiologist should understand, however, that this is not because of any lack of intelligence or industry on the part of the investigators but because of the nature of the subject. The soil flora, as a population, forms an extremely complex system, which is further complicated by the physical characteristics of the soil environment. Even if it were possible to distinguish and separate all the individuals, it would still not be possible to put this information together in such a way that the composite activity of the whole community could be seen or understood, any more than the economic life of a city could be developed by knowledge of the number of Jones, Smiths, dogs, and trees to be found therein, or a knowledge of what each might do if placed on an island in isolation. That which is possible for simpler microbiological systems is just not feasible for such a highly complex system.

There are other examples in microbiology which illustrate this fact. The bacteriologist has been quite successful in working out and controlling the active population in microbiological systems such as those involved in cheese-making, fiber-retting, or the production of sauerkraut, to name only three in which relatively simple mixed populations may be involved. He has been far less successful with more complex systems such as the intestinal flora of man or of chickens, the flora of the filter beds in sewage purification plants, or the rumen flora of the cow.

If it is true therefore that the classical analytical approach to the nature of the soil population is unproductive in the kind of information than can be used to solve problems of all sorts that are presented to the soil scientist, is it correct to assert so boldly that soil microbiology has a place in soil science? The evidence is not sufficiently overwhelming to justify rejection of this assumption. The fact that the microbiologists has not been able to make use of many of his data and observations in the solution of soil problems means merely that he started with an incorrect concept of the type of information that would be useful. There are kinds of soil chemistry and soil physics that have not proved re-

warding in terms of information enriching soil science, but the value of all soil chemistry or soil physics in application to soil science is not therefore discounted.

There is nothing at all original in these comments about the inadequacies of the methods available for studying the soil microflora. They were made most emphatically by Winogradsky more than 20 years ago. Winogradsky was perhaps the greatest of all soil microbiologists, but few of his contributions really dealt with the problems of soil science. He developed the so-called spontaneous culture method for encouraging the increase of any organism bringing about a process of interest in soil, but made relatively little use of this in his later work. His criticisms were valid, but for all his genius he did not really chart a way out of the wilderness.

Is there a way out, or are the difficulties insurmountable? In view of the ingenuity and elegance of many of the newer experimental procedures in biology, there is no need to take a deeply pessimistic view, though one must be a realist and recognize the shortcomings of much that has been attempted in the past. The way out probably lies in a combination of the biochemical treatment of the population as a whole, with pure cultural physiological studies of organisms that may be involved in whatever transformation is of interest at the moment. The potentialities and capabilities of the organism are determined; its nutritional requirements, the intermediate steps, and end products are ascertained. Then with this information available the same reaction is studied in the soil, possible intermediates are added, specific or nonspecific inhibitors, if available, are used, and a decision can then be taken as to whether this particular process in the soil proceeds in a manner that is consonant with the view that the pure cultural and the mixed cultural mechanisms are identical. This needs checking, not only when there is present a vast excess of the compound under study, as is the case in enrichment cultures or percolation procedures, but also at levels that more closely reflect the normal condition in soils. The soil microflora is ordinarily on a low-calorie diet. Normal renewal of the food supply through cropping or incorporation of residues of the vegetation, occurs only sporadically. Many of our soil microbiological experiments have been run at unreasonably high energy levels.

III. The Application of Microbiological Information to the Solution of Problems in Soil Science

In the previous section the thesis was developed that misconceptions as to the nature of the soil population and oversimplification in nutritional and environmental studies account in great measure for the

doubts that have been expressed as to the place of soil microbiology in soil science. Does this mean that microbiology is not going to contribute much to the unraveling of some of the important problems of soil science and agronomic practice that are known to involve microbiological activities? Is there no way of using much of the accumulated information about soil microorganisms in solving some of these problems? Some, indeed, seem to think that a great gulf lies between, a gulf that defies bridging. It is the contemplation of this gulf that has caused doubts as to whether microbiology is capable of giving information that will be helpful in relation to everyday soil problems. It would be difficult to sustain the argument that the only proper occupation of a soil microbiologist is to investigate processes or problems that relate directly to agricultural practices. There might be agreement, however, that such problems have all too infrequently been approached as vigorously and as doggedly as have more abstract, but very basic, studies relating to the physiology of certain soil organisms.

Consider the enormous efforts that have gone into the investigation of the mechanism of nitrogen fixation by nonsymbiotic organisms, and compare with this the volume of effort that has been brought to bear on one of the most important questions in soil science, whether in fact nonsymbiotic nitrogen-fixing organisms in soil in the field actually contribute significantly to the nitrogen economy of the soil and, if they do, how much, and under what circumstances. If critically examined the textbook dogma on the subject will be found to be most insecurely based. Because of the truly unique nature of the enzymic processes that must be involved, the nitrogen-fixing mechanism has been most appealing to some of the best microbiologists, who see it as the really key problem of these soil organisms, whereas the soil scientist, to whom the maintenance of organic nitrogen in soils under various kinds of land use is important, sees as the key problem the contribution which may be made by nitrogen-fixing organisms in soil in the field.

Currently the nitrifying organisms are receiving a good deal of attention again. The biochemical steps involved and the energy aspects are likely soon to emerge rather clearly. But although entirely relevant it is uncertain yet whether this information will much clarify some of the unsolved problems relating to nitrification in field soils, such as, for example, the situation in acid soils, in poorly drained soils, and in soil zones heavily charged with ammonia such as occur when fertilization with gaseous ammonia is practiced. Once again, there is needed a really vigorous attack at these field nitrification problems by a microbiological team, using to the full the best techniques and information available.

These two examples will serve to lead up to a point which has been

made before, that, although the establishment of the various steps in the nitrogen cycle was one of the great accomplishments of classical microbiology, the quantitative aspects of the nitrogen transformation in soil need careful re-examination and scrutiny. The conventional version may be an oversimplification. There are varying degrees of specialization in those groups of the soil population capable of carrying out the several steps in the cycle. The steps involving nitrate reduction particularly require review. There is probably less substance in the many statements about denitrification than in any other field of microbiology. This topic is reviewed in detail by Allison elsewhere in this volume. Advantage should be taken of new procedures. For example, it was most interesting to see that someone had thought it worth while to check the composition of soil air by infrared absorption, only to find present a significant amount of nitrous oxide. At high moisture levels the amounts increase rapidly but even at low moisture content very slow evolution of this gas takes place. If this is so, the soils of the earth may well be the source of supply of the nitrous oxide in the atmosphere.

There does seem, therefore, to be a little evidence of unwillingness or reluctance among microbiologists to tackle some of the more practical yet vital problems of soil science or to push their findings to those logical conclusions that may influence agronomic practice.

Another field, currently of substantial importance, where the microbiologist is not yet playing the part that he should, is in connection with the stability, persistence, accumulation, or disappearance in soil of the many organic compounds developed for use as herbicides, fungicides, insecticides, etc. In some cases, persistence or moderate persistence is desired, and the effectiveness of the treatment may depend on it; in other cases slow or even rapid disappearance may be desirable. The fate of such compounds, though ultimately decided by their microbiological availability, may be further complicated by adsorption by clay or organic colloids, or removal downward by leaching. The exotic character of many of these compounds makes the problem all the more intriguing, because there may have to be a lag phase or adaptive phase of considerable length before decomposition at a significant rate takes place. Some workers in this field have put a good deal of effort into the isolation of the active organisms, which is the classical bacteriological approach, and one which opens up interesting physiological avenues, but may not provide answers to the specific problem that formed the starting point. The really significant questions which relate to the employment of these compounds may be left to others who cannot do more than approach them empirically.

It would be inappropriate to conclude on this note of mild criticism without making reference also to the other possibility referred to in the introduction, namely, that there has been some lack of appreciation or understanding of the contribution of microbiology to general soil problems.

One of the really significant advances made in the understanding of soil processes in the last 25 years is the recognition of the complete interdependence of the carbon and nitrogen cycles, the carbon and phosphorus cycles, the carbon and sufur cycles, and so on. This can be stated in another way, namely, that there cannot be decomposition without concurrent synthesis, or there cannot be dissimilation without concurrent assimilation. The quantitative aspects of the interdependence are reasonably well worked out for nitrogen, but less completely so for phosphorus, sulfur, or other nutrients. However, it is in effects on supplies of available nitrogen and phosphate that organic matter transformations affecting yield are most influential. Most of the shorter range effects of different rotational systems on yield are reasonably predictable from existing information. Considerable time, effort, and money could probably be saved in this type of work if full advantage were taken of microbiological advice before commencing such experiments. The microbiologist should not be scolded or chided for unhelpfulness if his help is not sought.

To attempt to give a forthright answer now to the question "What is likely to be the place of microbiology in soil science?" would clearly be futile. So much yet remains to be done. There is one area, in particular, developments in which might weigh considerably in the answer. This is an area that has as yet been investigated realistically by very few microbiologists. It involves the signficance of interactions between organisms in the soil, and between soil organisms and crop plants. It is impossible to deny that antibiotic substances are produced by many microorganisms that occur in soils. It is possible to demonstrate the presence of some antibiotics in soil. It is reasonable to assume that the production of such compounds may well affect the nature of the active flora, which otherwise would be determined primarily by the nutritional status, which in turn may be greatly affected by the presence of plant roots. The active microbial complex is a team, fitting together in such a way that the metabolic activities of its members together utilize the energy sources efficiently. Production of antibiotics may disrupt or distort the team structure. Some workers, and seemingly particularly those with the greatest experience in the study of antibiotics, seem inclined to discount their significance in soil processes for a variety of reasons, perhaps the chief of which is that antibiotics are not uni-

versally effective, so that there will always be present some organisms that are unaffected and which may utilize the antibiotic itself as an energy source. Whatever may be the answer to this, it does seem that insufficient attention has been given to possible direct effects of compounds produced by microorganisms on root elongation, root growth, and root function. There is some risk in leaving out of the calculations just the organism in which there is most interest, namely, the plant. Root elongation, and particularly that of seedling roots, is affected, almost always adversely, by extremely low concentration of many microbial products and some antibiotics. Conversely, there are in the literature many references to favorable effects in plant growth produced by organic manures or humus constituents, that cannot be accounted for solely by the inorganic nutrients supplied. These more subtle relationships between plants and microorganisms deserve the very best study that can be brought to bear upon them. They may well account for some of the hard-to-explain differences between soils and between soils differently cropped.

IV. Epilogue

This review is unsatisfying in that no straightforward answers are given to the wholly reasonable questions "What place does microbiology have in soil science?" and "What is likely to be the place of microbiology in soil science?" The discussion of these questions has consisted in part of explanations and alibis. There is little doubt that the frustration felt by some soil microbiologists as they try to evaluate the progress made through a microbiological approach to some of the tougher problems of soil science is very real, and has infected some of their colleagues in other branches of soil science, who therefore tend to discount or overlook the microbiological nature of many soil processes. Together this may contribute to the impatience with which the subject is regarded in some administrative circles, which in turn has reflected adversely on the support available for such work in this country. No battles were ever won by armies in a defeatist frame of mind. Nor is there any justification for defeatism; it is no discredit that there may have been some false starts; it is no discredit that some of the viewpoints and hypotheses have been found incorrect. Biology as a whole is advancing at a rapid rate. Tough as are some of the problems in soil science, there is no good reason for assuming that they are far more intractable or refractory than those in other areas. A science that is now immature may be expected to mature.

In the meantime all who are soil scientists or whose work involves soils should never overlook the fact, abundantly established, that the

soil is a living system with a dynamic population, nutritionally competitive and highly responsive to changes in its food supply, and that there are few problems in soil science in which the role of the soil inhabitants can be ignored. Microbial participation or involvement, directly or indirectly, should be assumed until proved otherwise. The cropping of soils presents very special microbiological situations that relate in part to the effects of the crop and its residues on the microflora, and in part on the activities of the organisms in influencing the physical and nutritional environment for the plant.

References

The nature of this paper is such that direct citation to original work is not feasible. Instead there is listed below a number of papers which survey the progress of research in soil microbiology, or in major fields thereof, and in a few of which attempts are made to evaluate the contributions which such work may make to soil science.

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